



A compact immersion grating spectrometer with quantum capacitance detectors for space-borne far-IR spectroscopy Progress Report

P.M. Echternach
C. M. Bradford, T. Reck, B. Pepper,
Jet Propulsion Laboratory, California Institute of Technology

Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson



Immersion Grating Spectrometer with Quantum Capacitance Detector Readout

PI: Pierre Echternach - JPL



Description and Objectives:

- We are developing an immersion R~ 500 grating spectrometer using a readout based on a novel detector based on superconductor pair-breaking in mesoscopic superconducting devices for the far-IR submm spectral range under very low levels of illumination. We will demonstrate a fully multiplexed 256 spectral channel device with shot noise limited detectors for wavelength between 200 and 350 μm .

Key Challenge/Innovation:

- The key innovation of this device is the combination of a curved grating spectrometer fabricated in silicon and the use of the extreme sensitivity of a quantum system to the external environment as a detection mechanism to build a detector with exquisite sensitivity.

Approach:

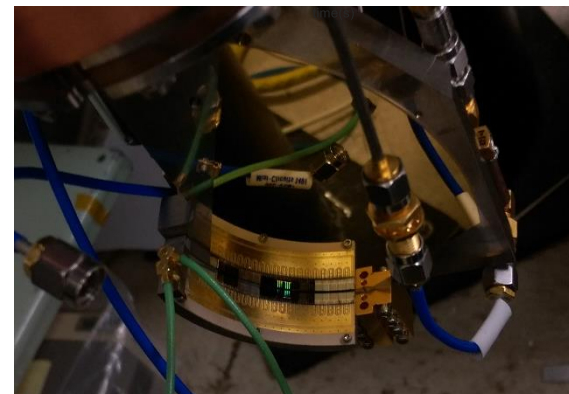
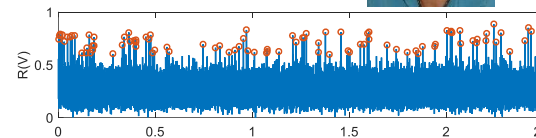
- Separate development of wafer spectrometer using characterization by a network analyzer.
- Optimization of stand alone Quantum Capacitance Detectors.
- Development of coupling scheme between spectrometer and QCDs
- Multiplexed readout based on ROACH system

Key Collaborators:

- C.M. Bradford
- Theodore Reck
- B. Pepper, JPL

Development Period:

- Oct 2013 -Oct 2017



Accomplishments and Next Milestones:

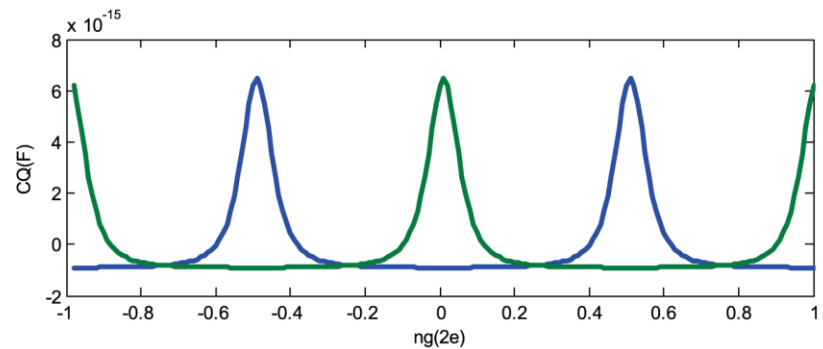
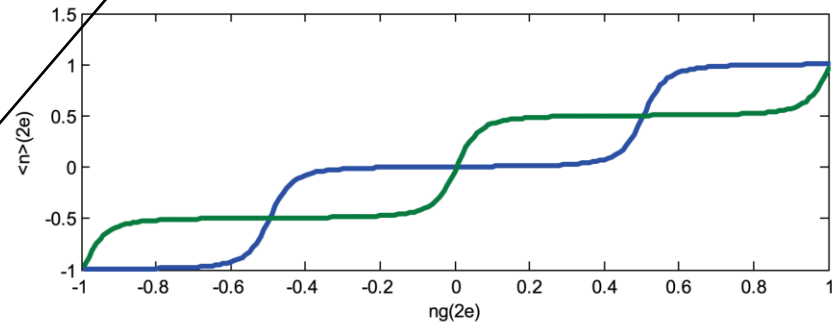
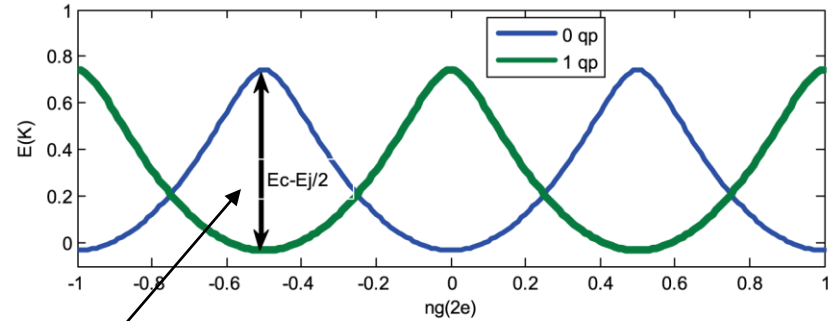
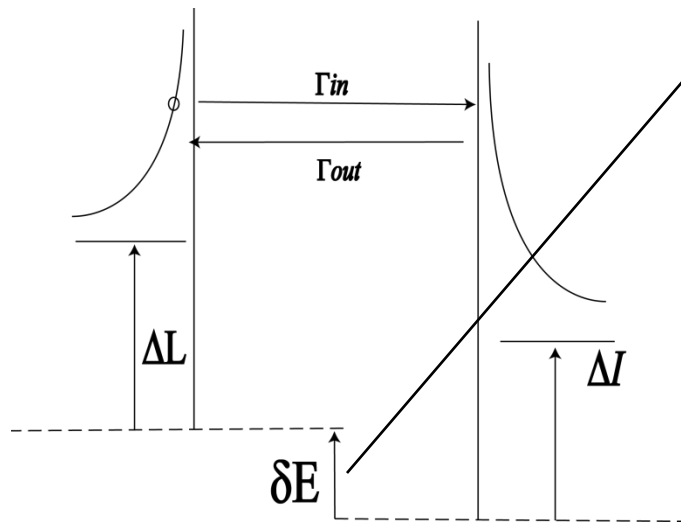
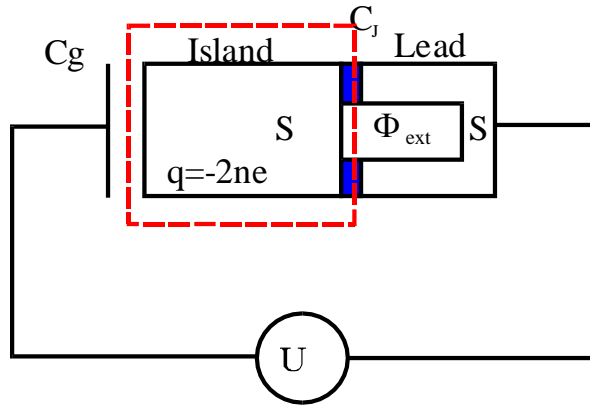
- Demonstrated photon shot noise limited performance at 200 μm at 0.1aW with 30- 60% end to end efficiency
- Demonstrated first prototype wafer spectrometer R~ 600
- Completed design of integrated spectrometer
- Demonstrated Single Photon detection of 1.5THz radiation
- Future milestones
 - Demonstrate fully integrated spectrometer
 - Expand multiplexing factor to 256

Application:

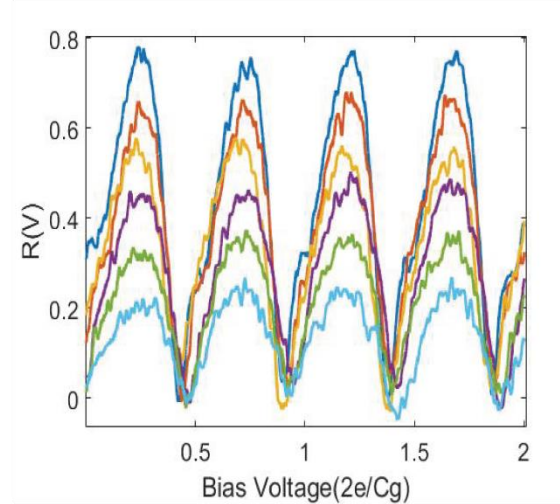
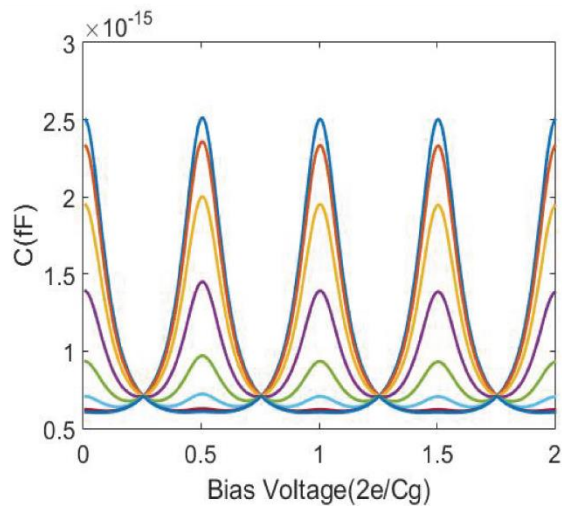
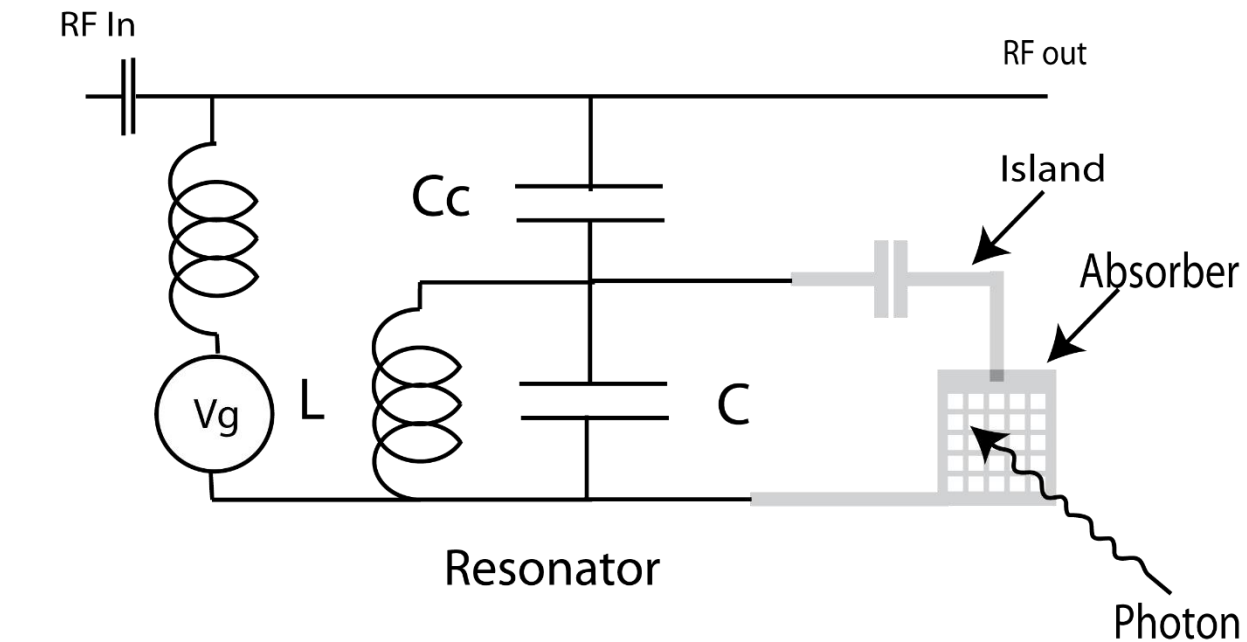
- Future space telescope – SPICA, Origins Space Telescope
- Balloon experiments

TRLin = 1 TRLcurrent = 2 TRLtarget = 4

Single Cooper-pair Box (SCB)



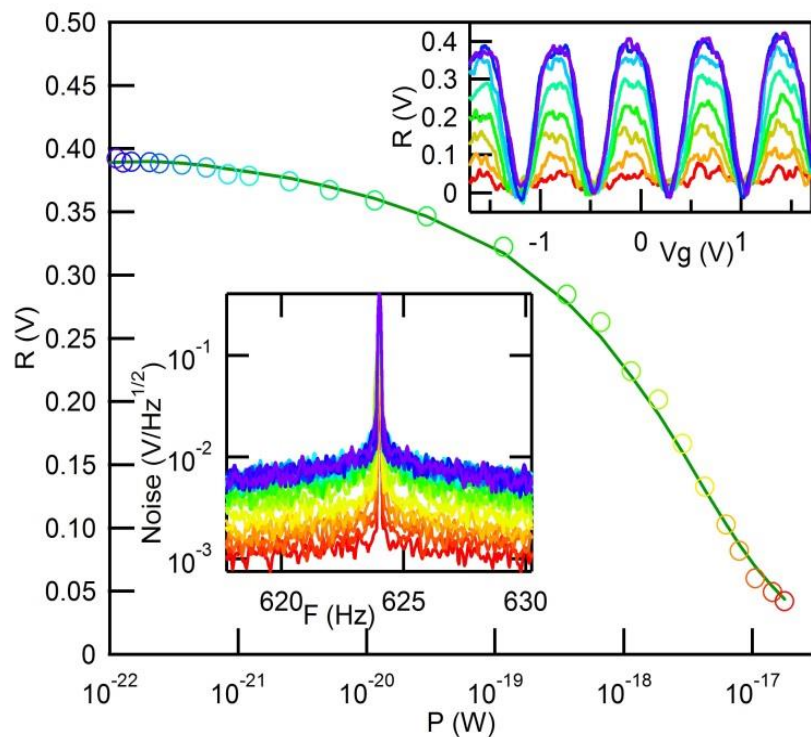
Quantum Capacitance Detector



The Quantum Capacitance Detector

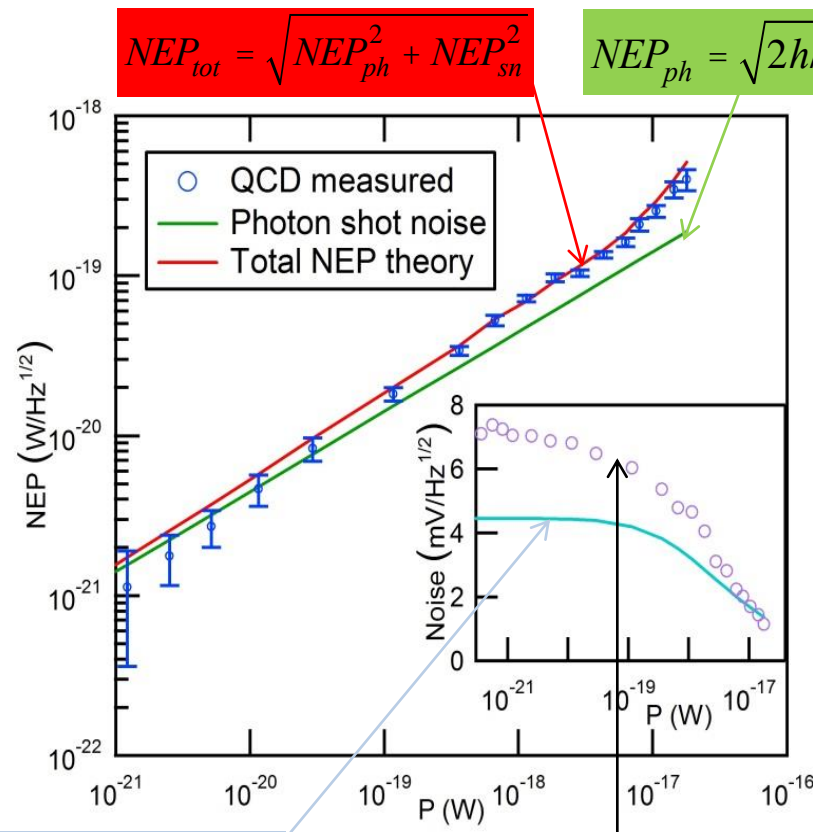
NEP as a function of optical signal
Photon shot noise limited!

Response and noise as a function of optical signal



Shot noise of electron tunneling

$$S_{sn}(f) = \sqrt{2A^2 (\Gamma_{in} \Gamma_{out} / \Gamma_{\Sigma}) / (\Gamma_{\Sigma}^2 + (2\pi f)^2)}$$



Total measured noise

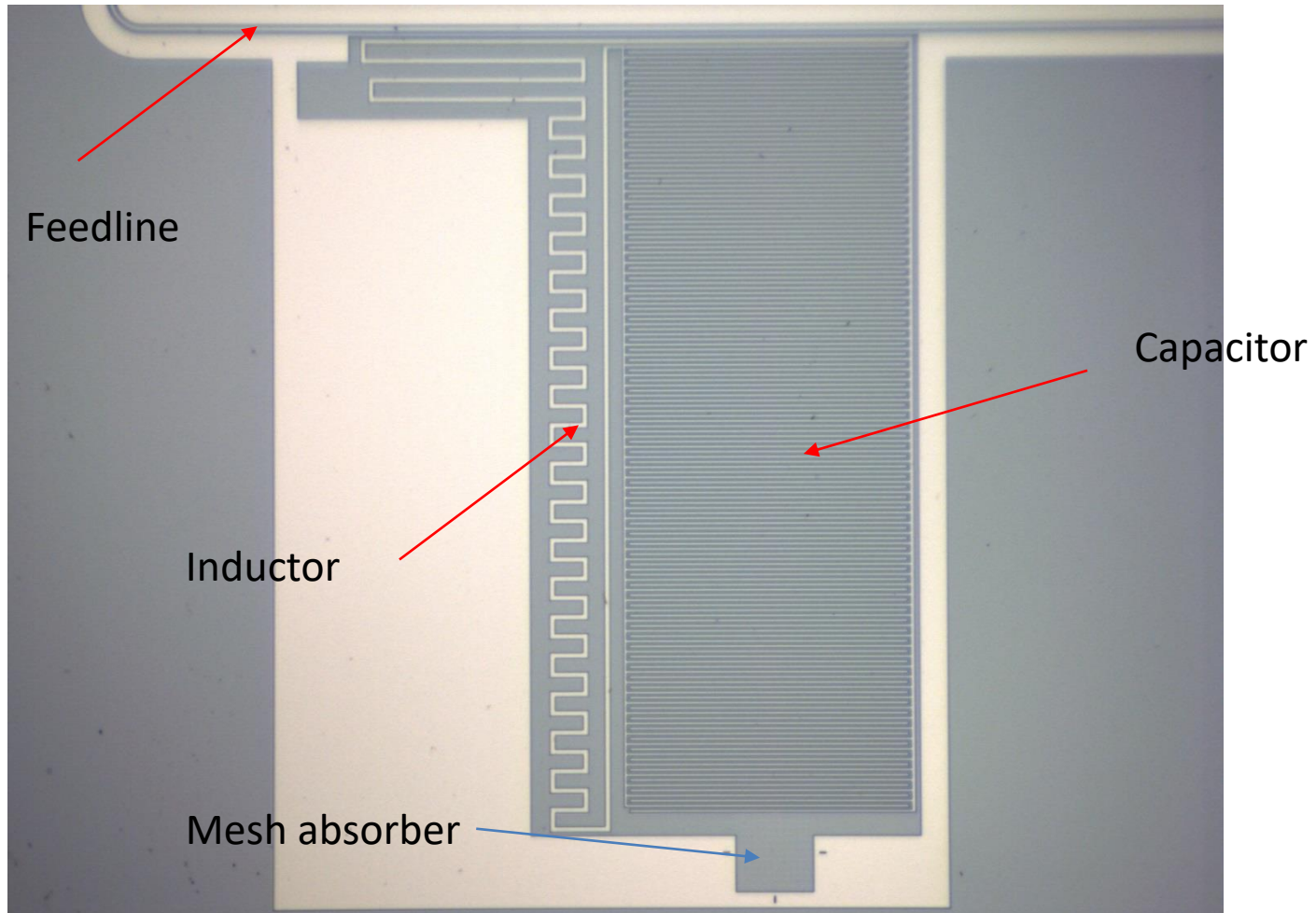
$$NEP_{SN} = S_{SN}(f) / \left(\frac{dR}{dP} \right)$$

$$NEP_{tot} = \sqrt{NEP_{ph}^2 + NEP_{sn}^2}$$

$$NEP_{ph} = \sqrt{2\hbar n P_s}$$

Lens coupled mesh absorber LEQCD

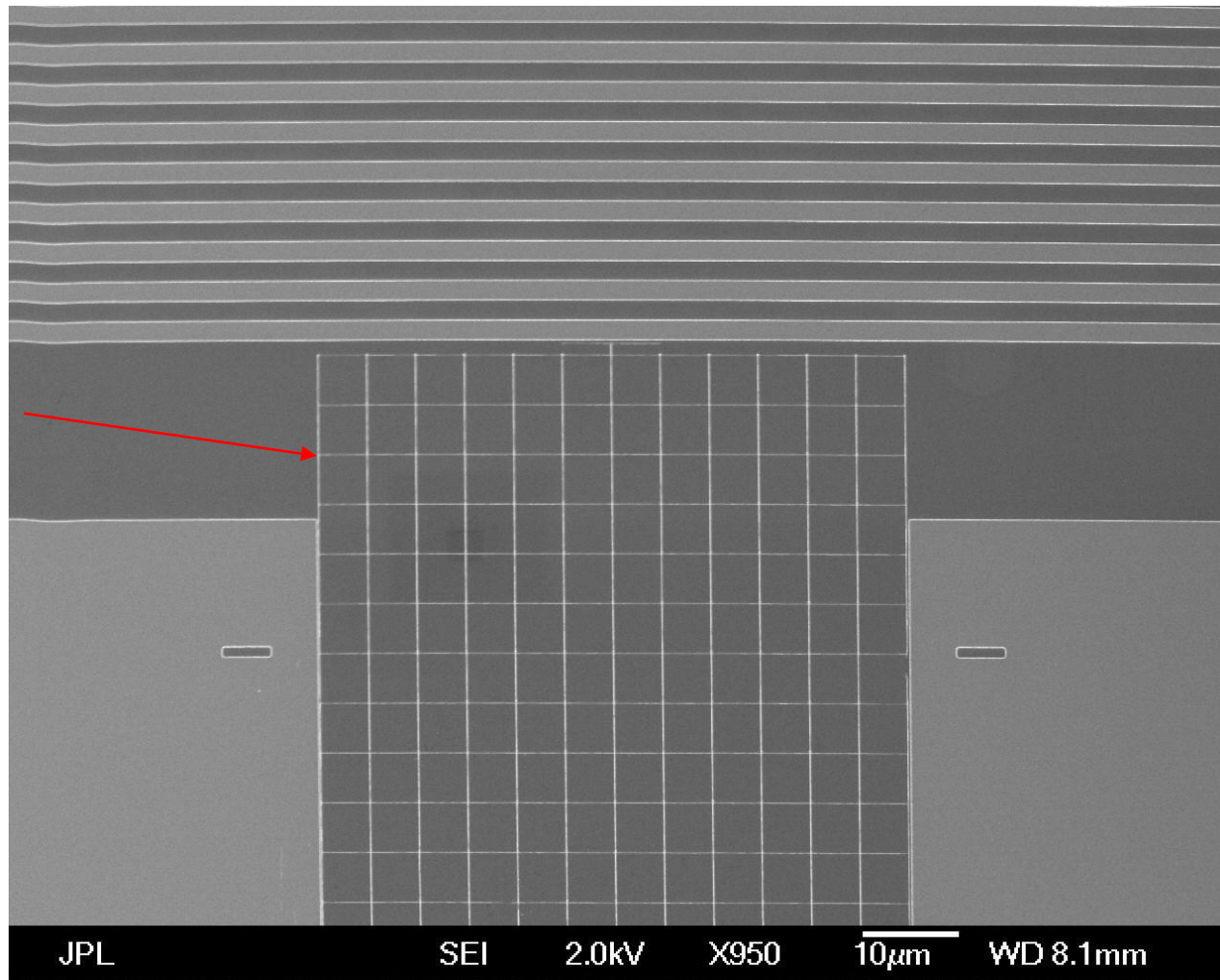
- Need mesh absorber instead of antenna to better couple to spectrometer modes
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator



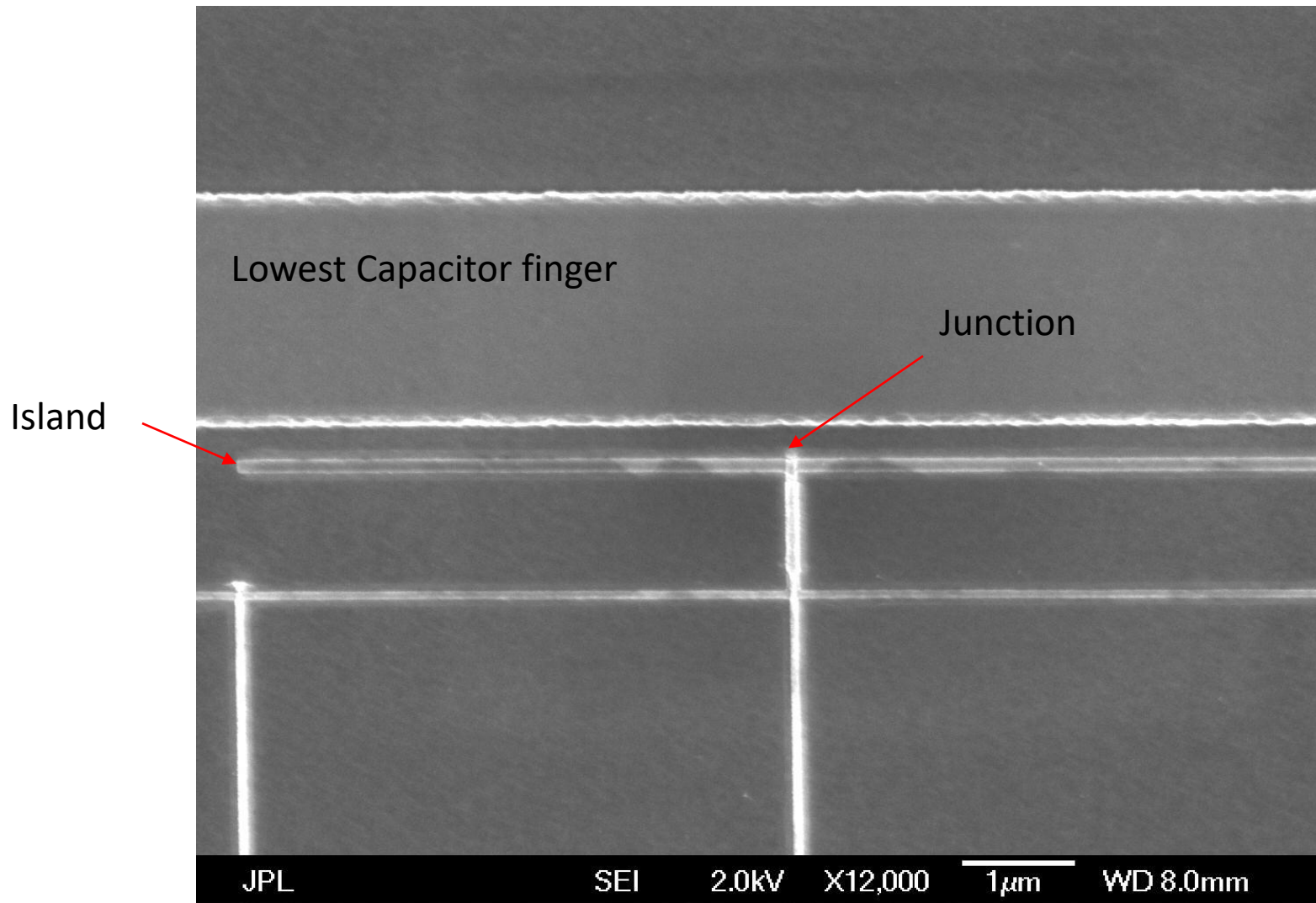


Lens coupled mesh absorber LEQCD

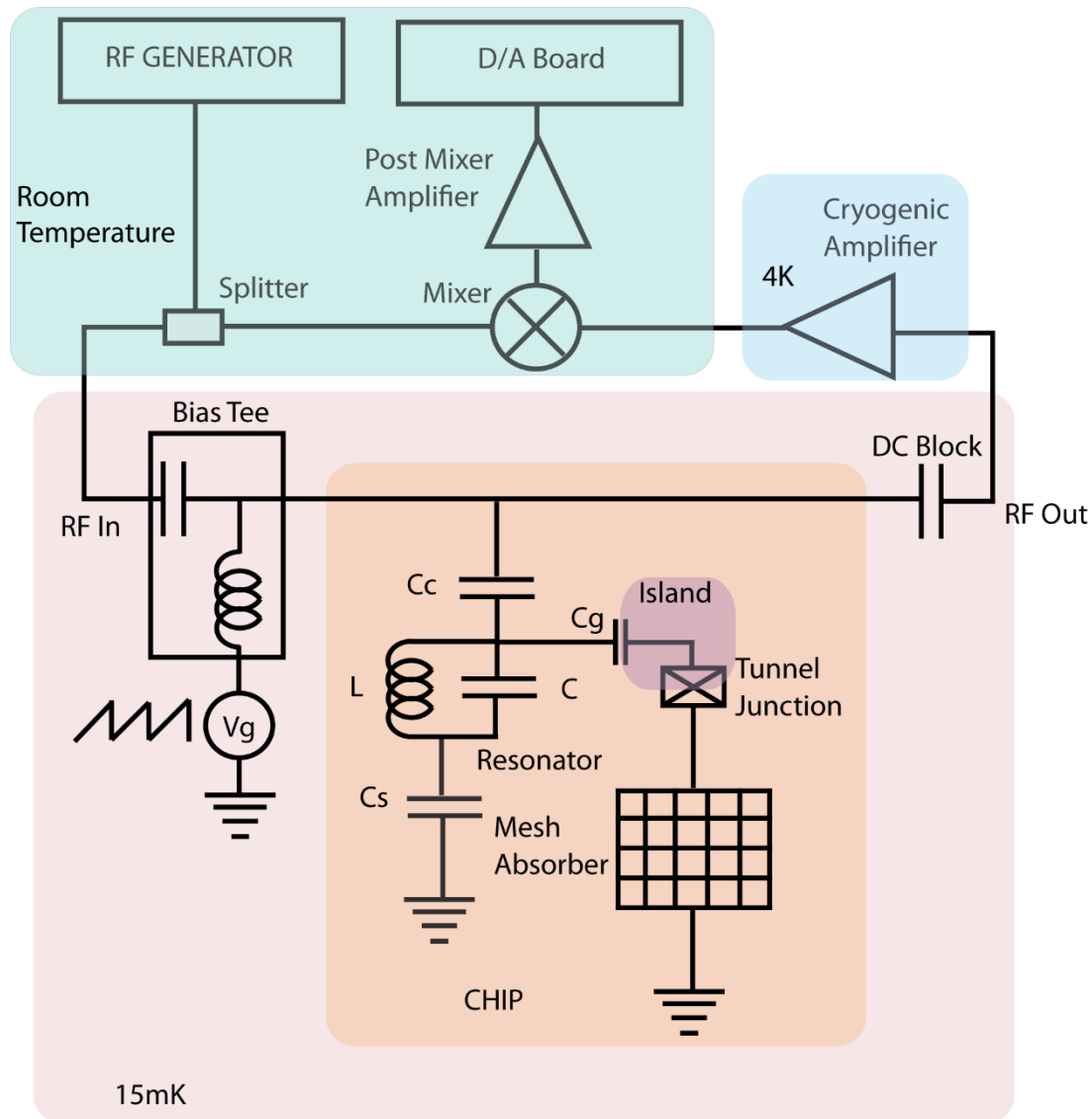
Mesh
absorber



Lens coupled mesh absorber LEQCD

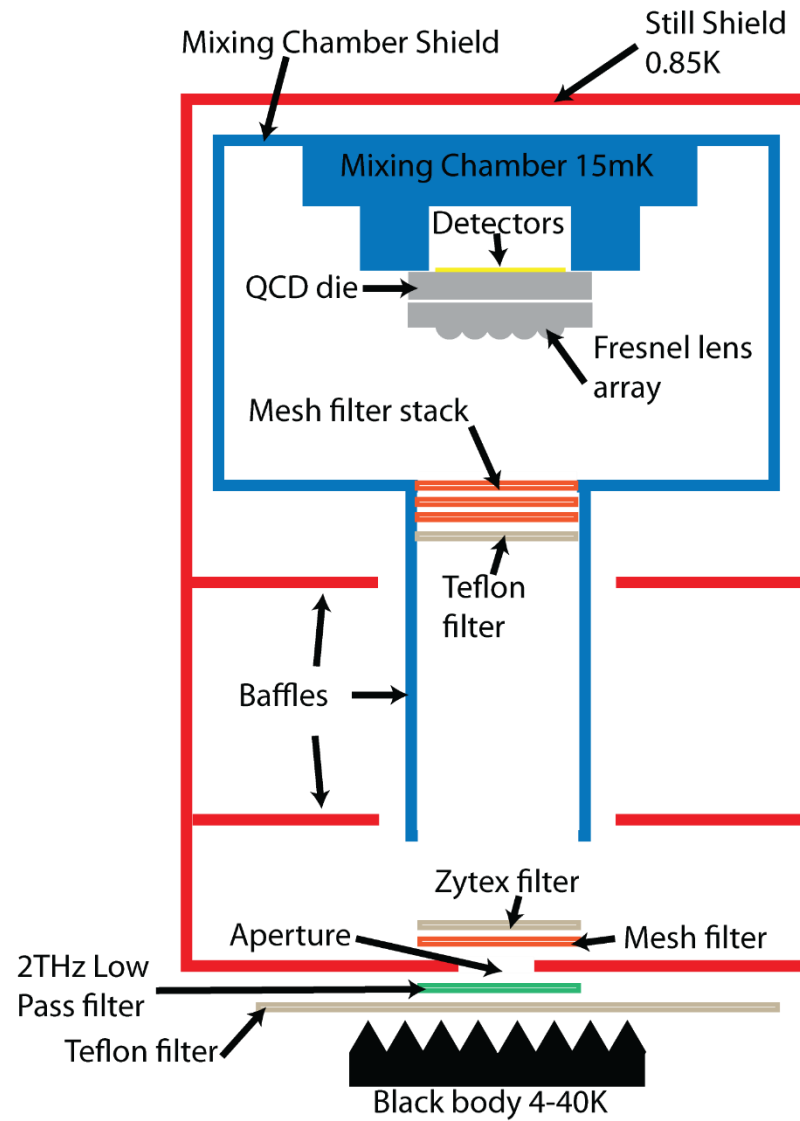


Measurement setup





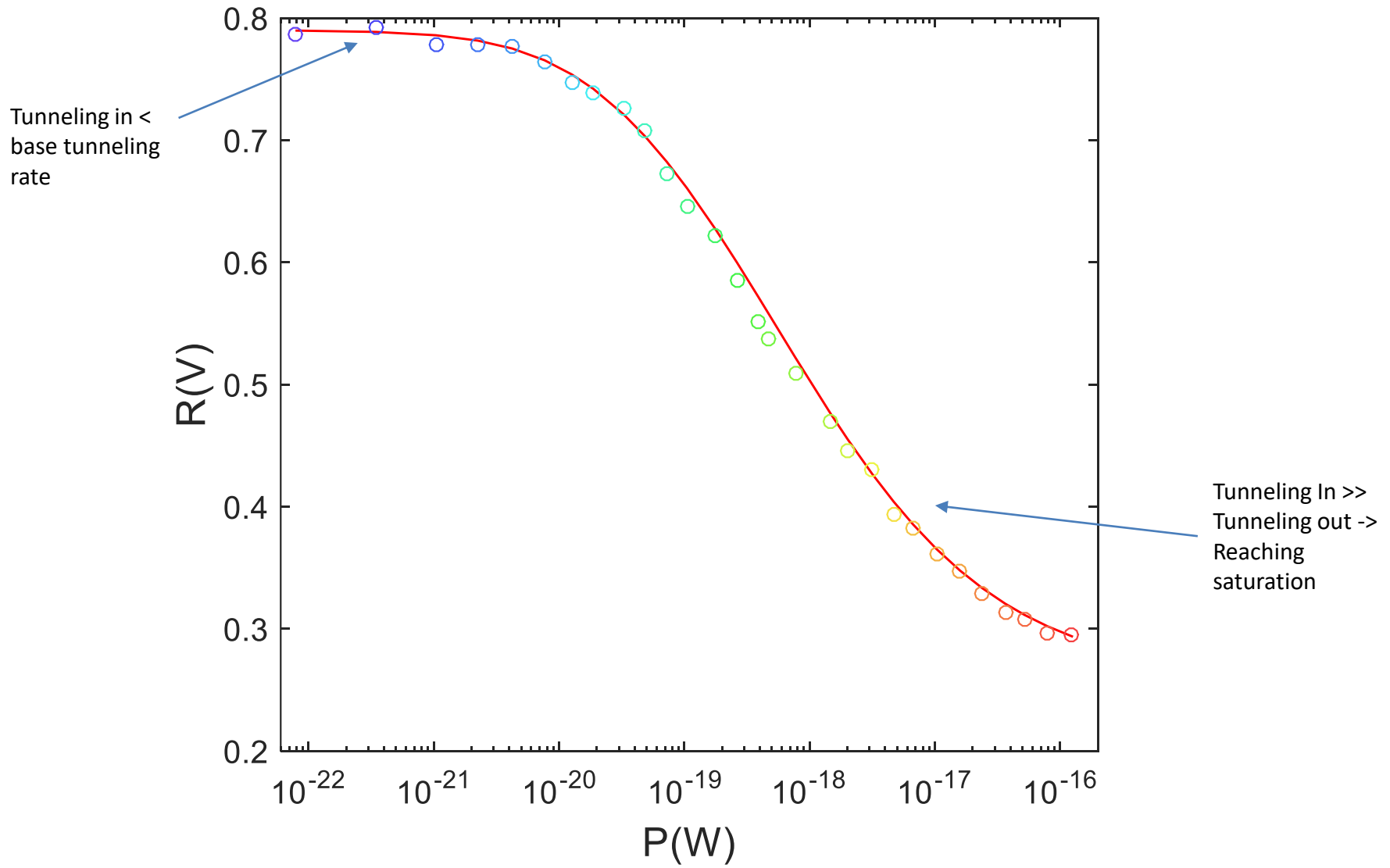
Measurement setup





Lens coupled mesh absorber LEQCD

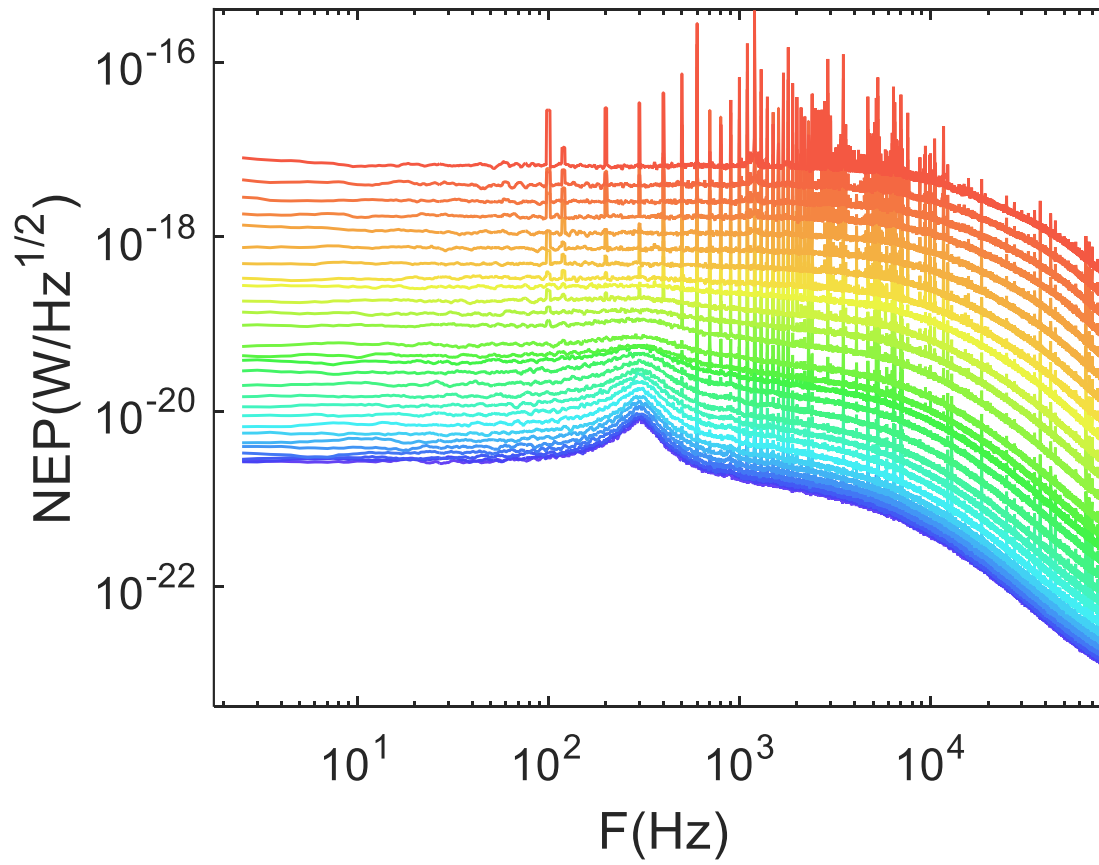
- QCD response as a function of optical power





Lens coupled mesh absorber LEQCD

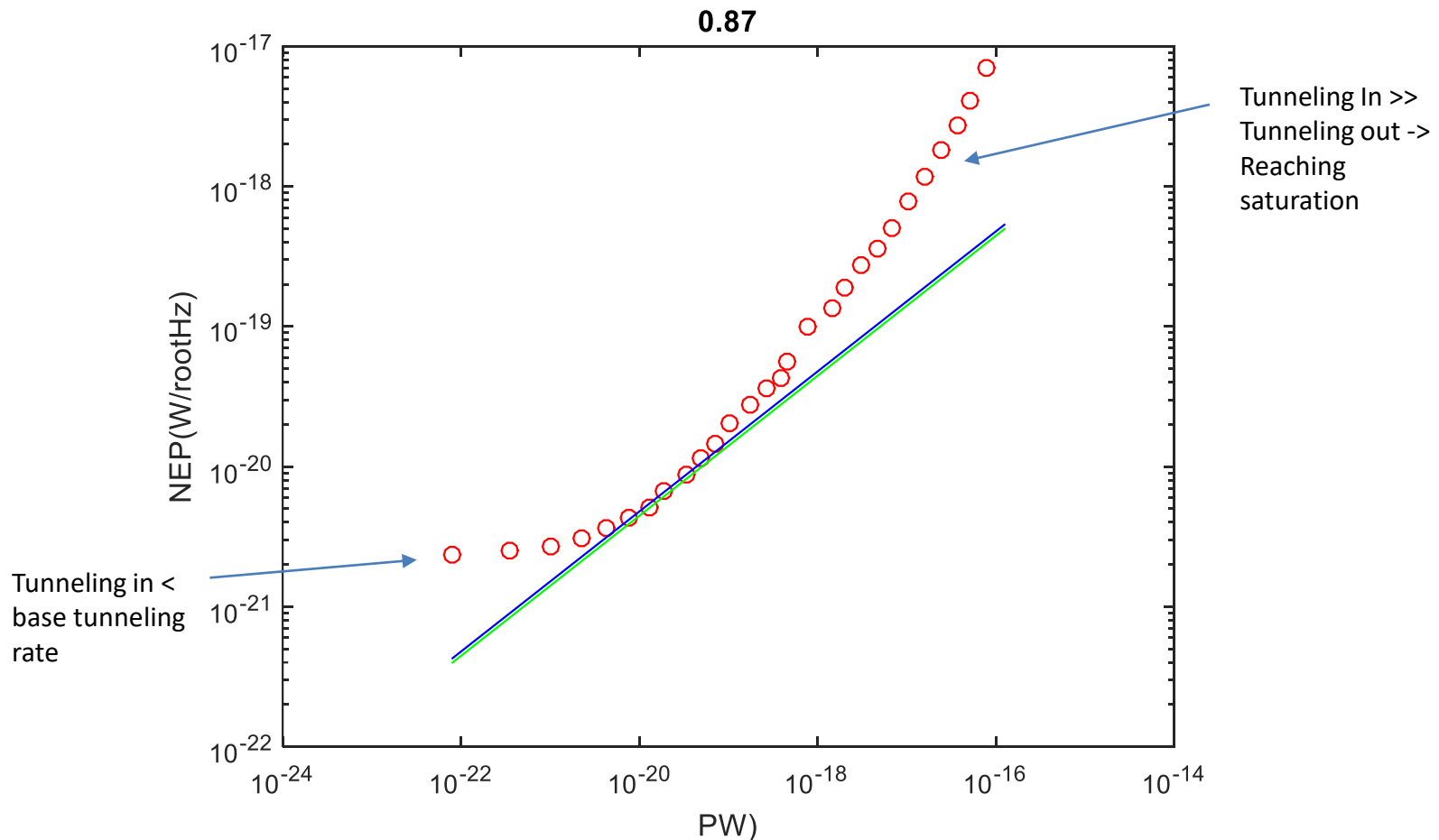
- NEP for various levels of optical illumination



- PSD time span 2s
- Gate sweep frequency 100Hz
- One sweep = 6 peaks
- QC peaks = 600Hz



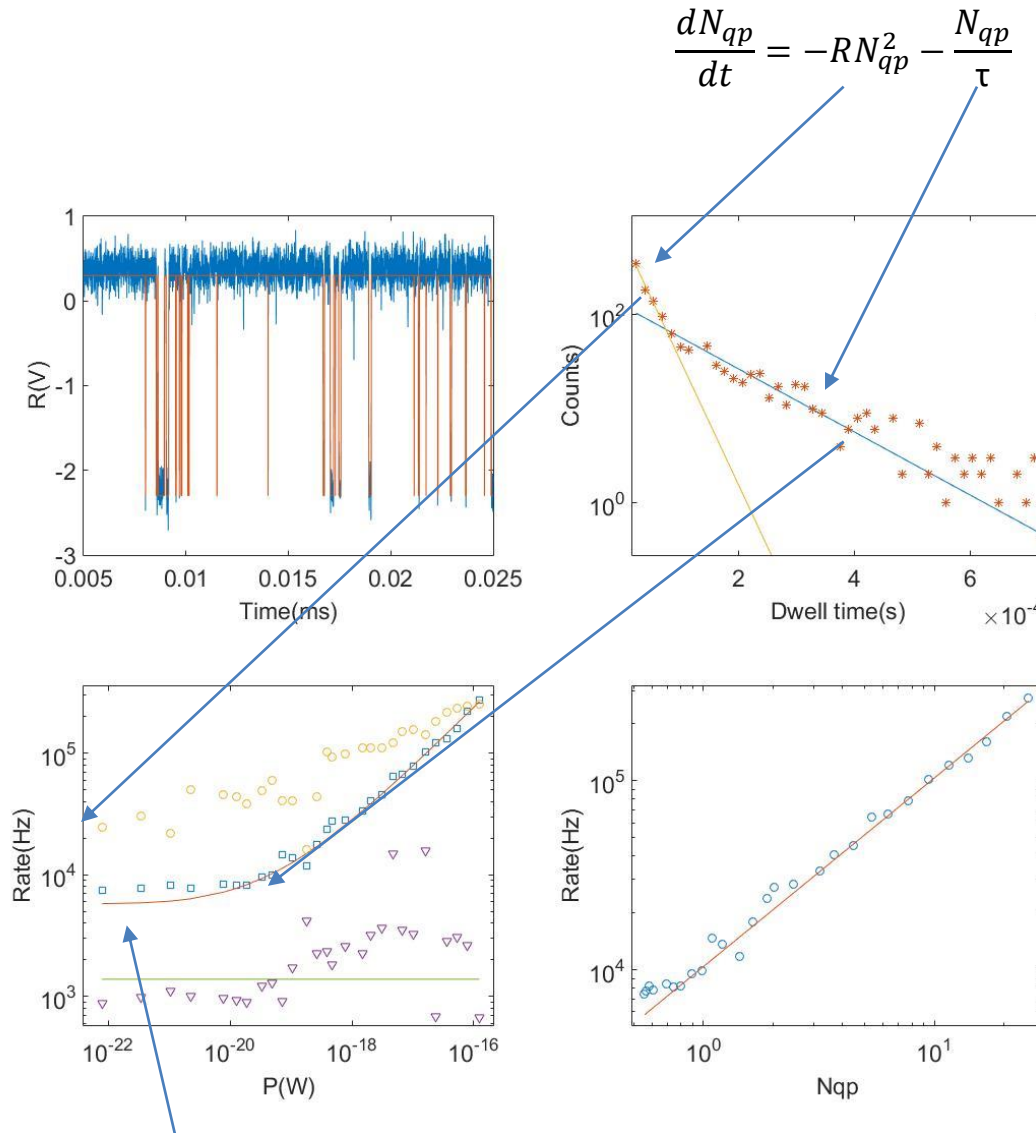
Lens coupled mesh absorber LEQCD



- $P^{1/2}$ dependence implies photon noise limited performance
- Efficiency extracted from ratio of measured NEP and photon shot noise NEP
- Should be able to detect single photons



Search for Single Photon Events – clues from DC biased time streams



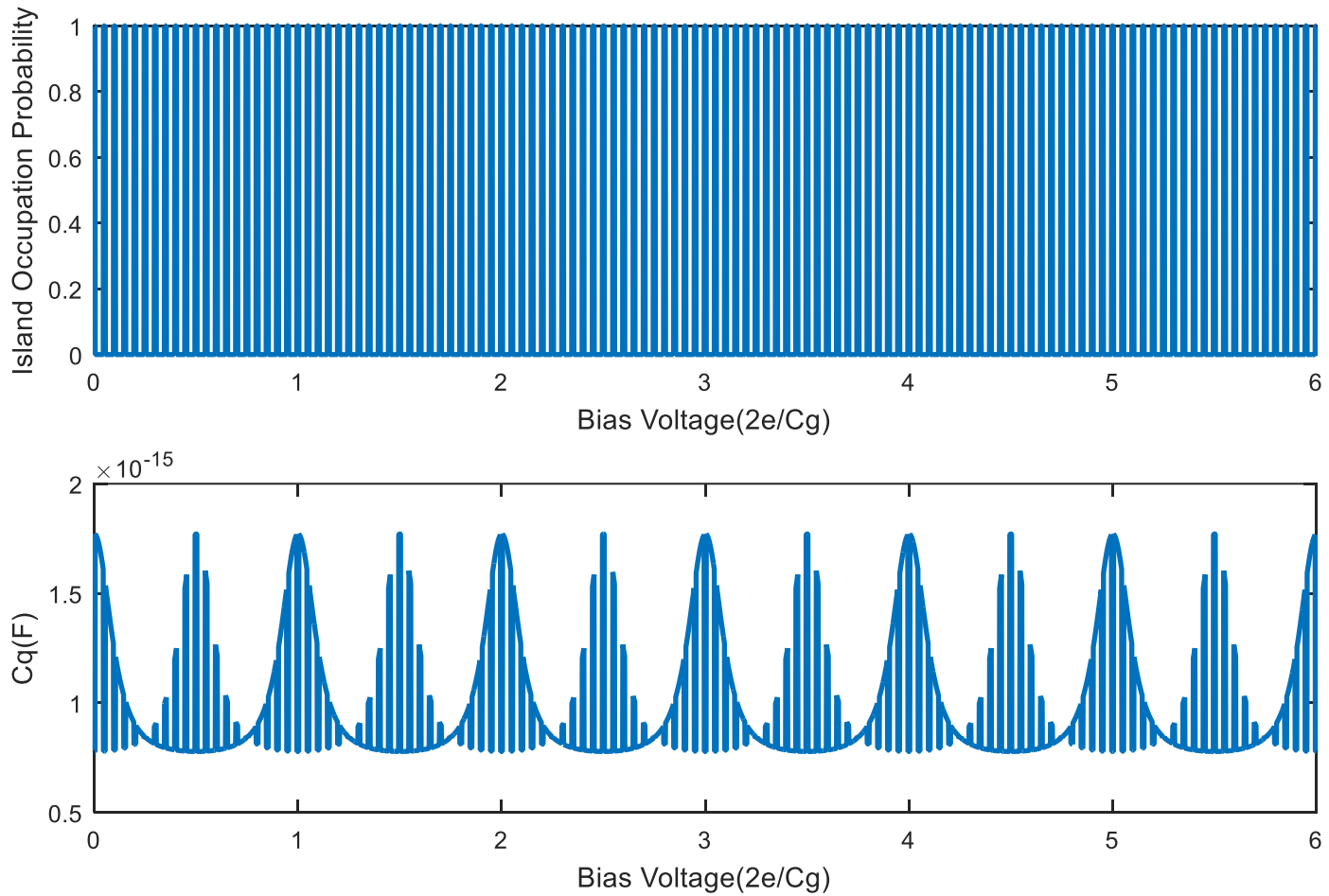
Background tunneling
rate ~ 8kHz

- Measure time trace while DC biased
- Obtain histogram of dwell times
- Fit histogram to exponential decay
- Rate for longer times is due to residual lifetime
- Faster rate at shorter times due to single photons
- Tried to look for those faster events in smaller chunks of time stream – DAQ rate not fast enough to get good signal to noise ratio
- Can estimate how fast the initial tunneling rates are from the measured tunneling rates versus number of quasiparticles
- One photon generates on average 20 quasiparticles=> instantaneous rate about 220kHz



How to filter out background tunneling

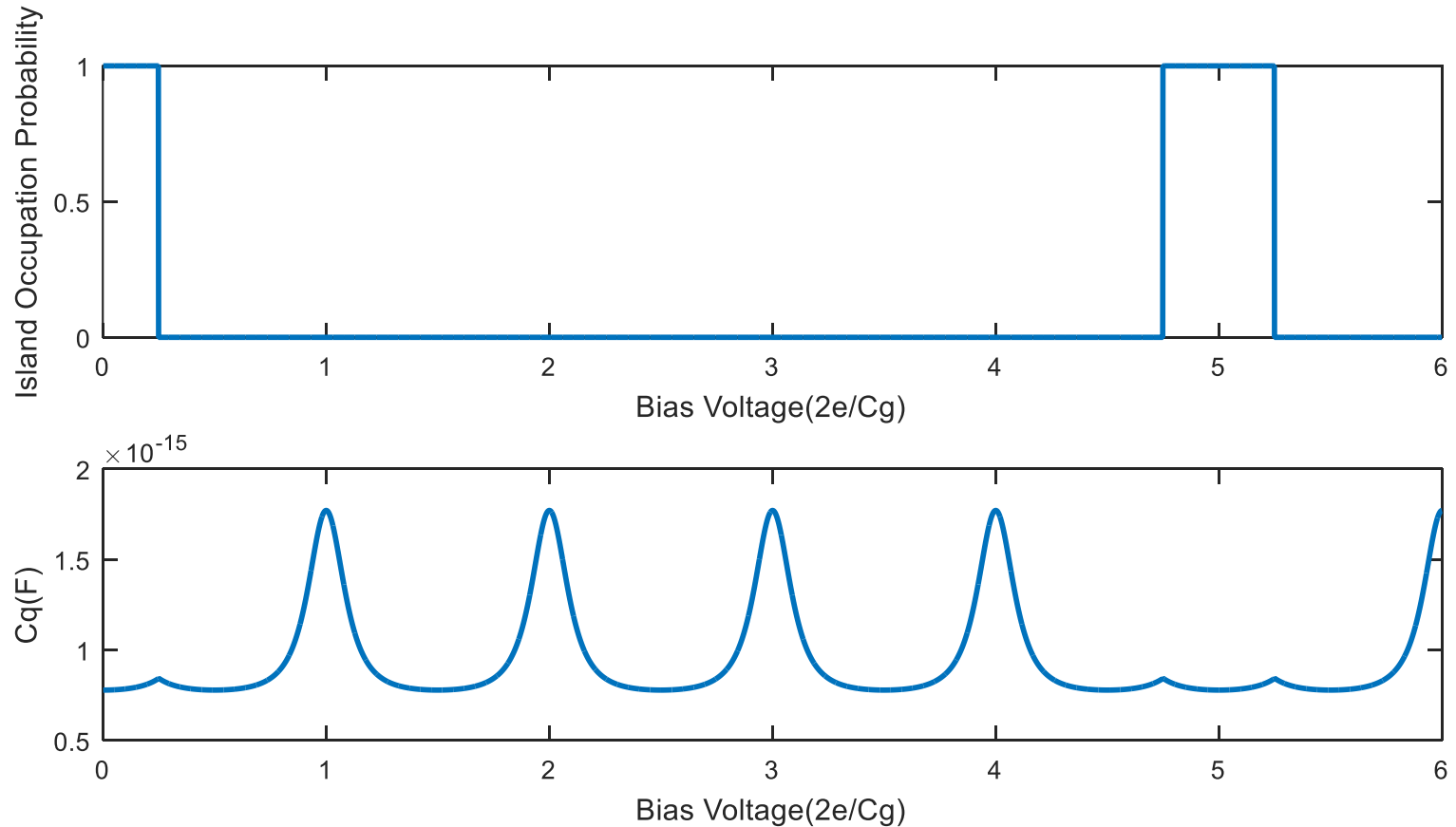
Gate sweep frequency \ll Tunneling in rate





How to filter out background tunneling

Gate sweep frequency > Tunneling in rate – effect of photon absorption

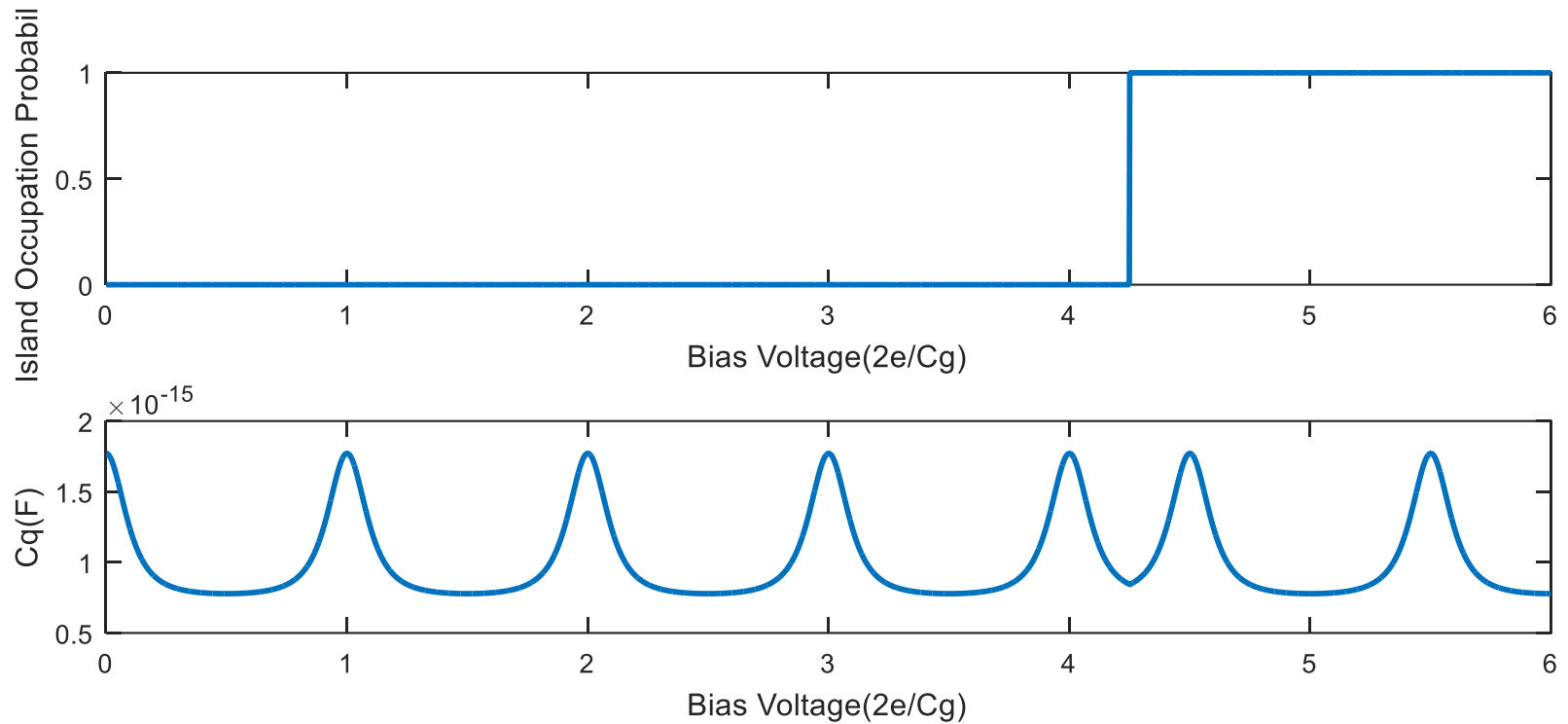




How to filter out background tunneling

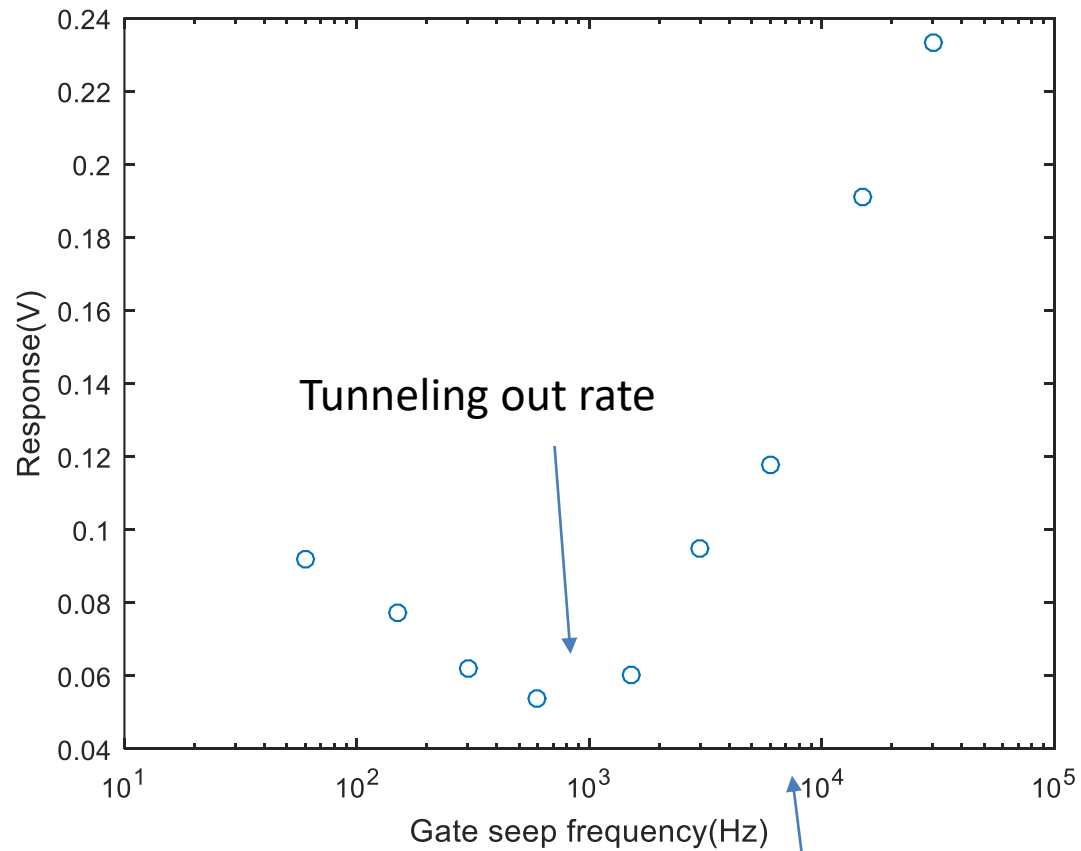


Gate sweep frequency $>$ Tunneling in rate – effect of background tunneling = e-shifts





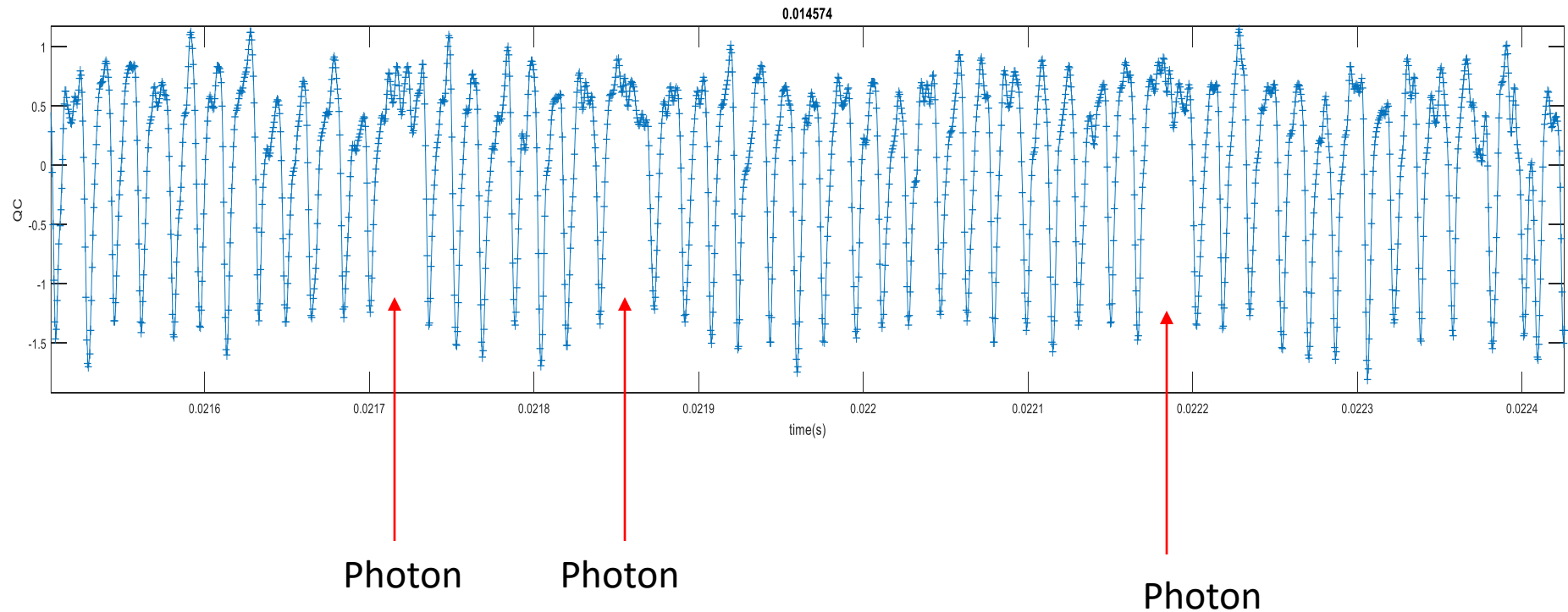
How to filter out background tunneling



Background tunneling in
rate

“Fast sweep reveals single photon events spoiling QC signal

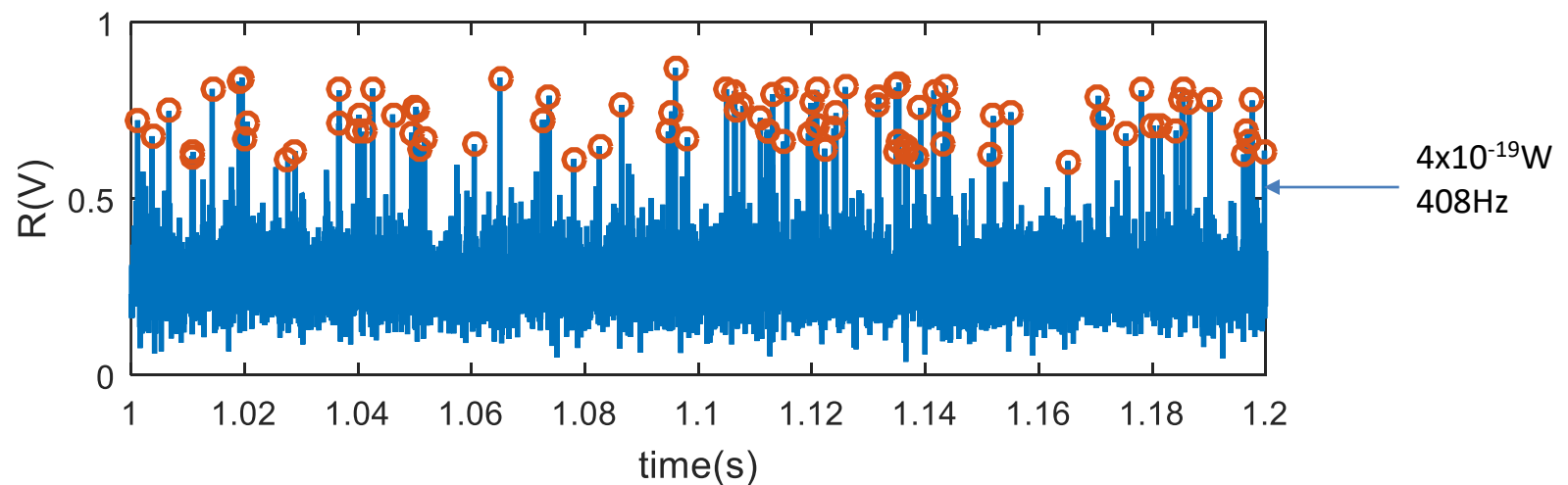
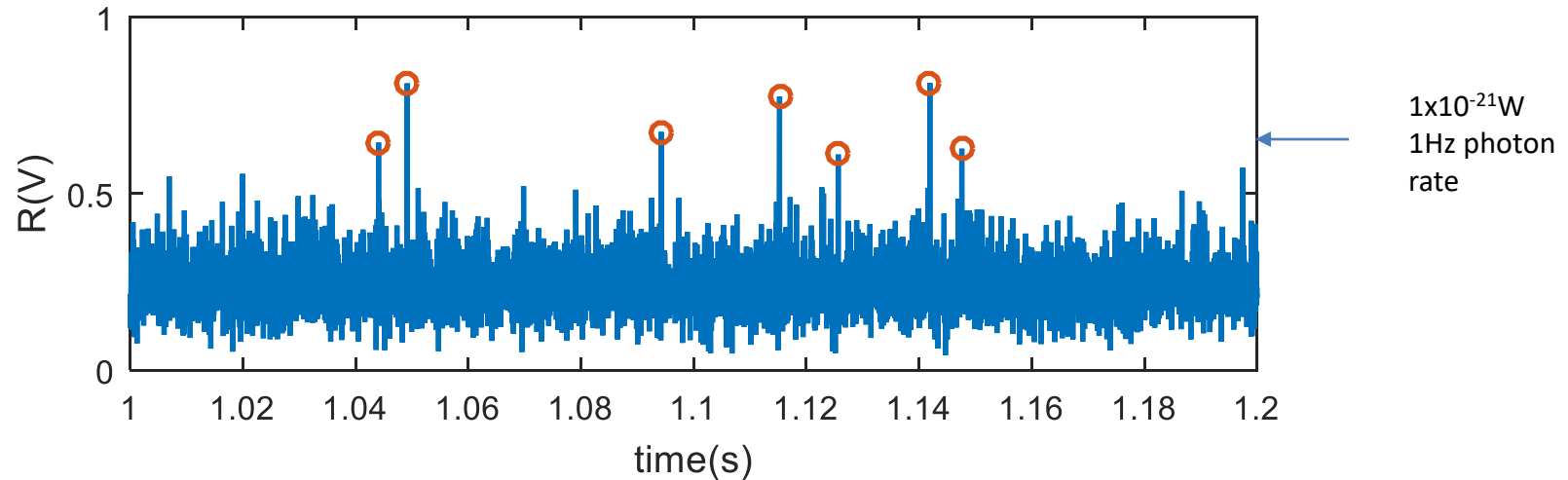
- Sweep rate $\sim 22\text{kHz}$ spanning 3 Quantum Capacitance Peaks \Rightarrow effective sweep rate $\sim 66\text{kHz}$
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal
- Therefore Gaps should be due to single photon absorption





Variance evaluated in 30 us bins shows photon events

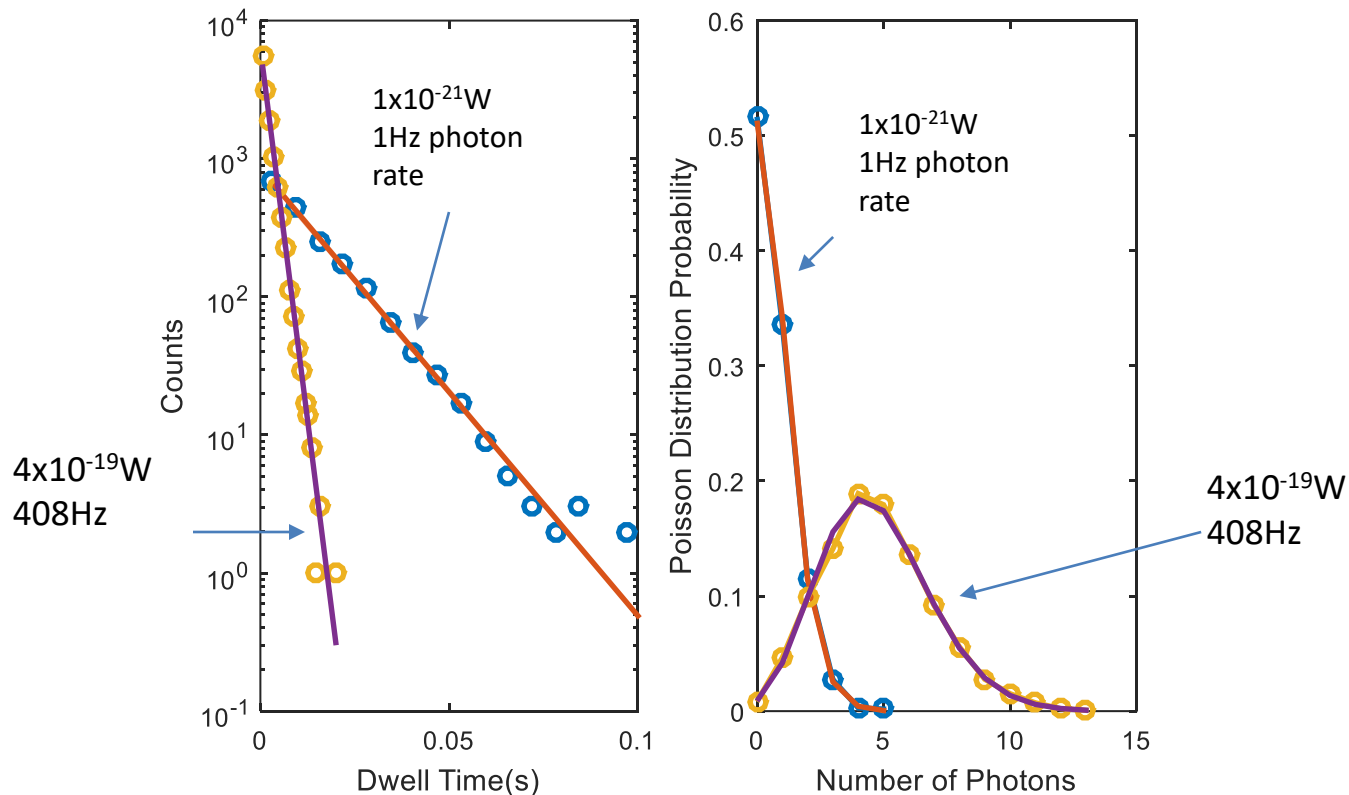
- From time traces calculated variance of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts) – slices are 30 μ s long
- Subtracted this trace from the maximum of the traces
- Gaps in the Quantum Capacitance trace will show up as peaks
- Repeat for different black body source temperatures





Photon arrival intervals follow Poisson statistics

- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons within a time interval 36ms (Arbitrarily picked)
- Plot probability x number of photons; blue circles is measured, lines are calculated Poisson distribution probability (no fit, just using measured average number of photons)



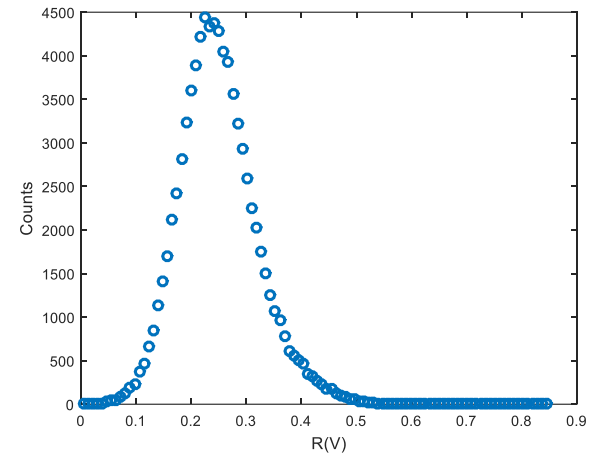


Photon arrival statistics

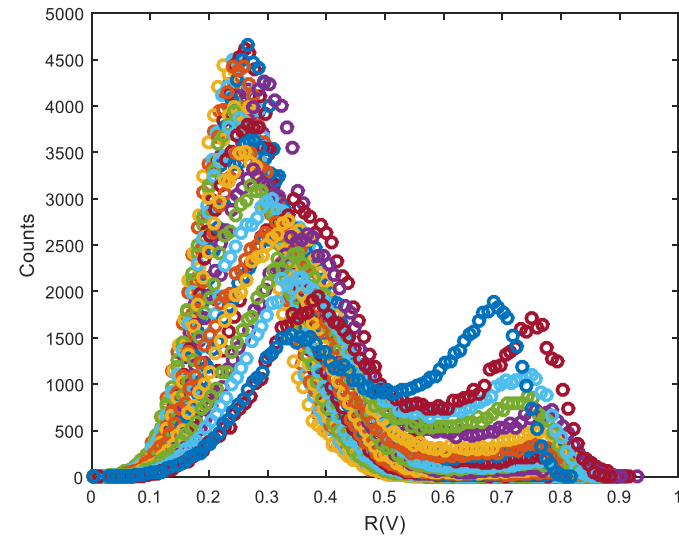
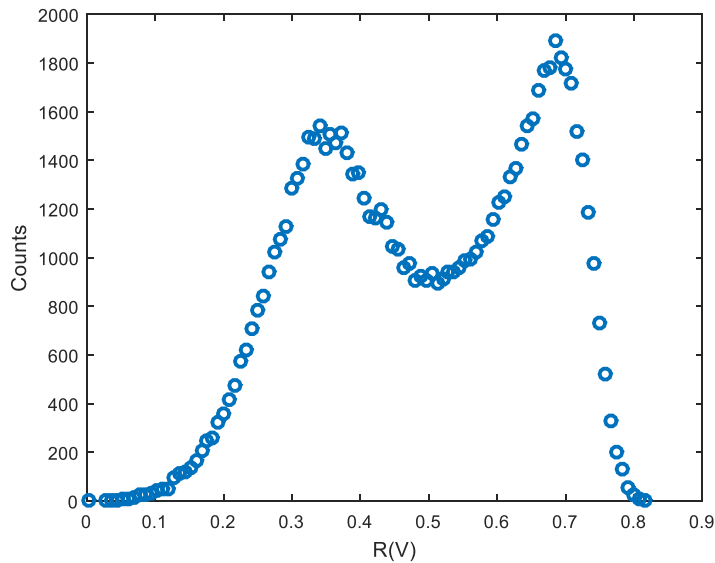


Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body

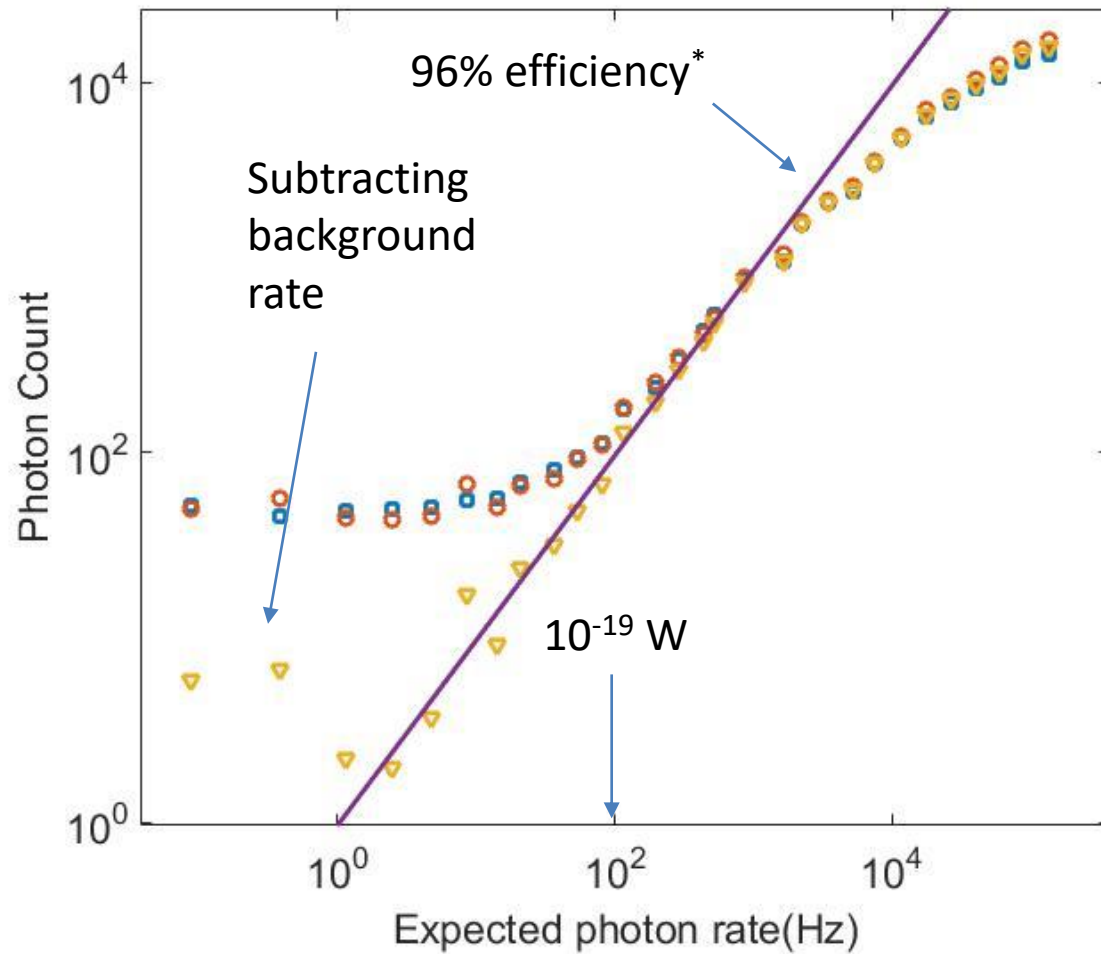


Hot black body



- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

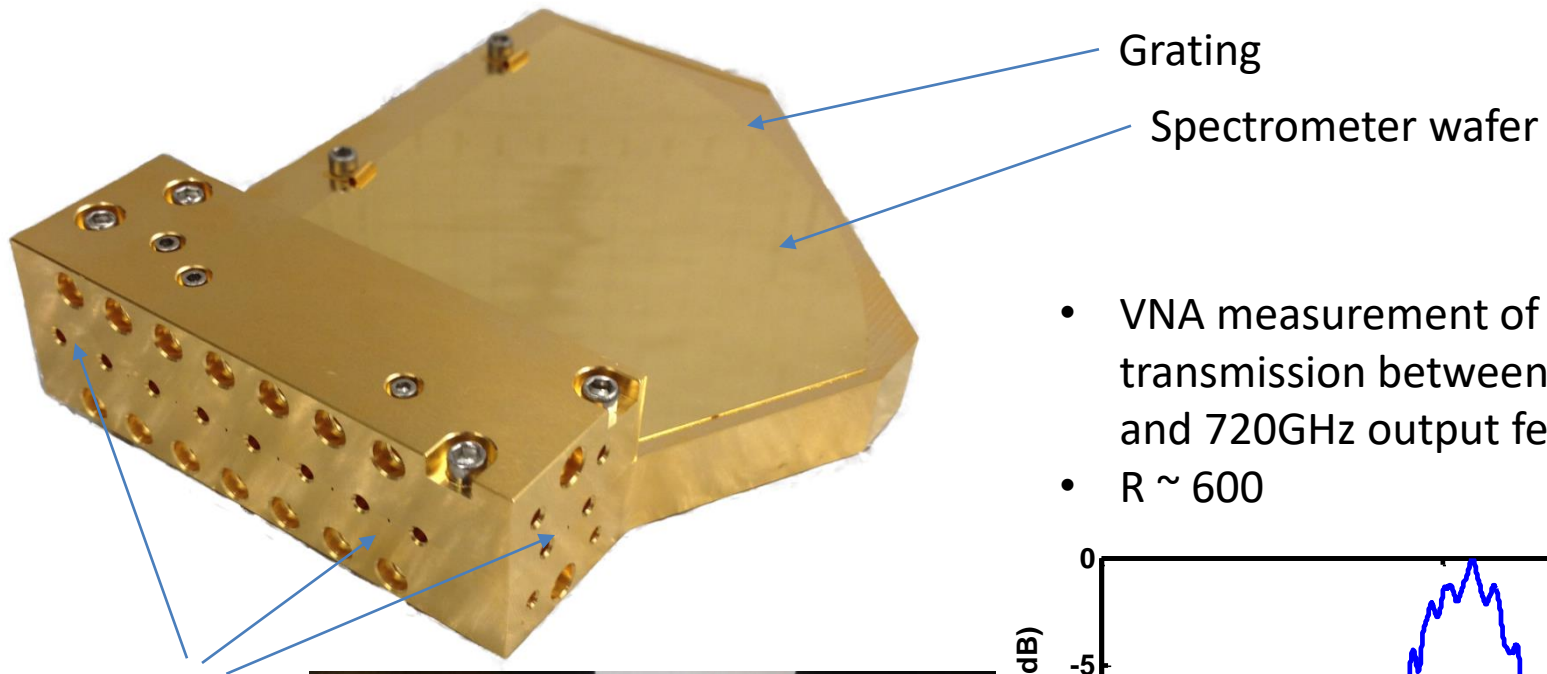
Counts of response between 0.6 and 0.9 versus number of expected photons



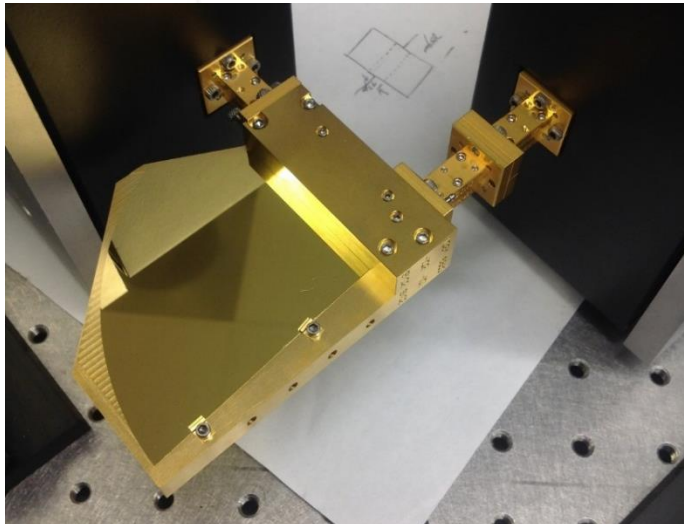
- Efficiency will decrease with when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks

* With respect to absorbed power

Grating spectrometer on a wafer

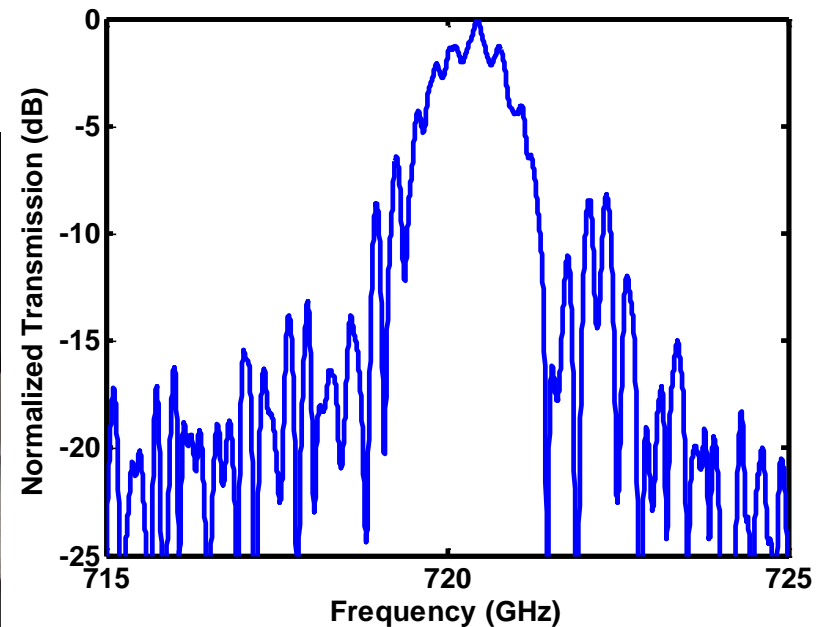


Waveguides



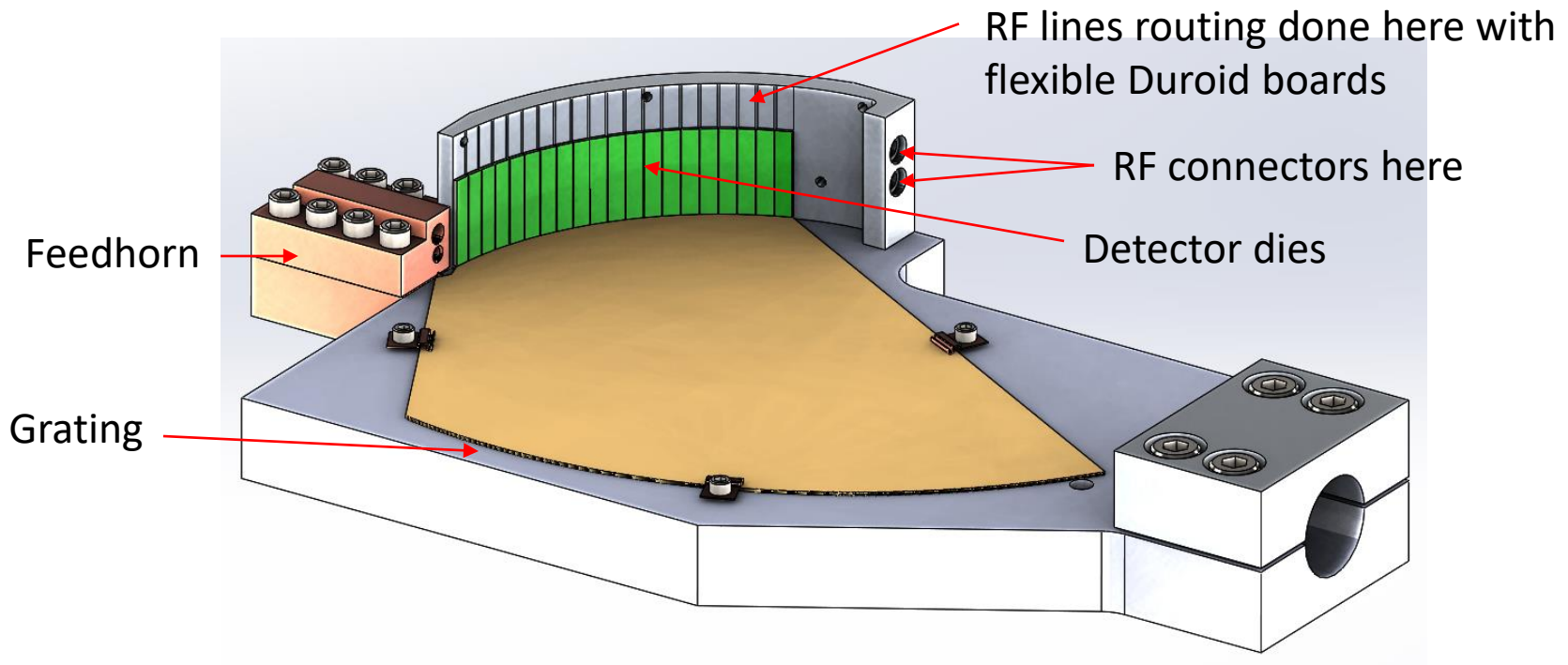
Connected to vector network analyzer

- VNA measurement of transmission between input feed and 720GHz output feed
- $R \sim 600$

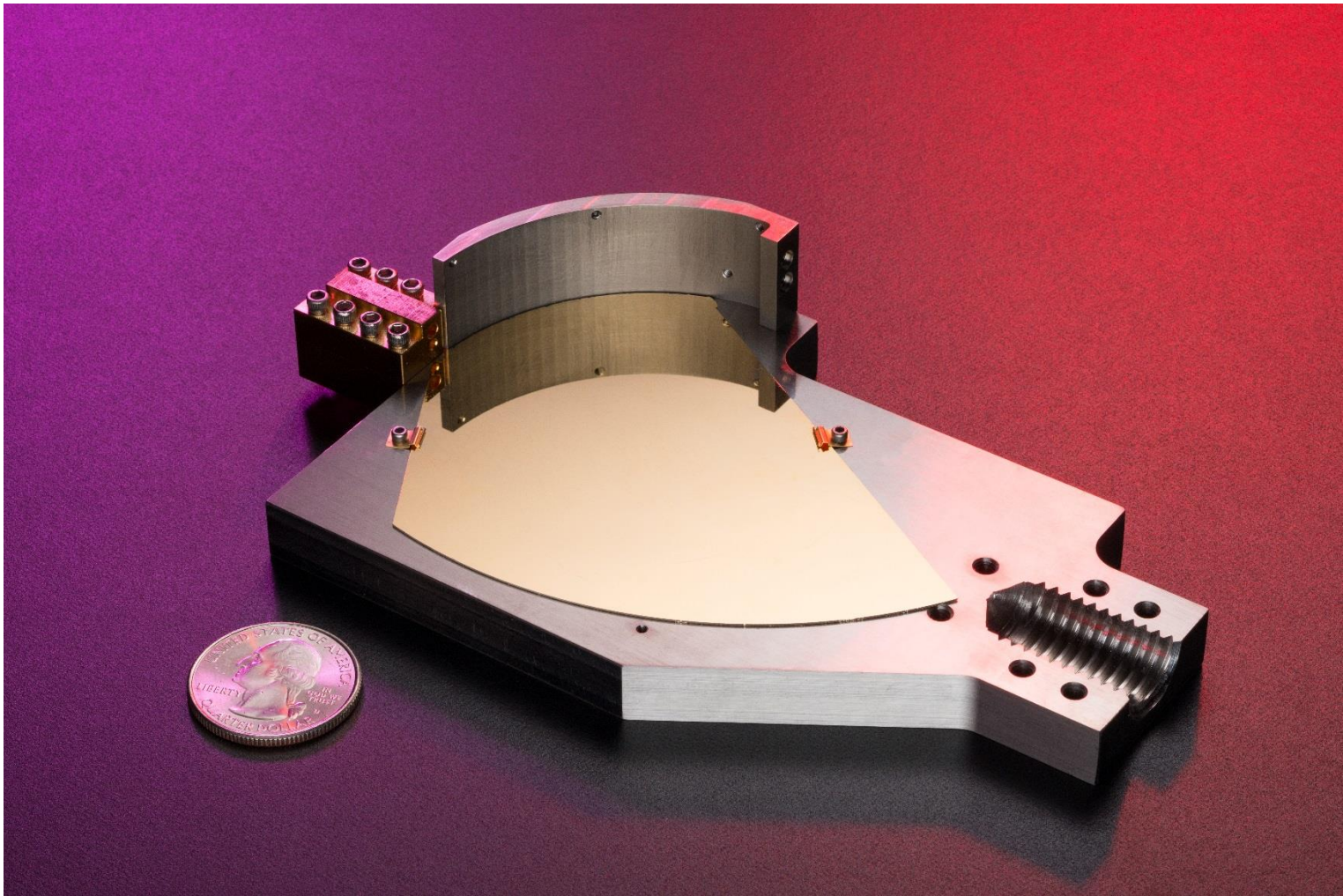


Integrating Spectrometer and QCDs

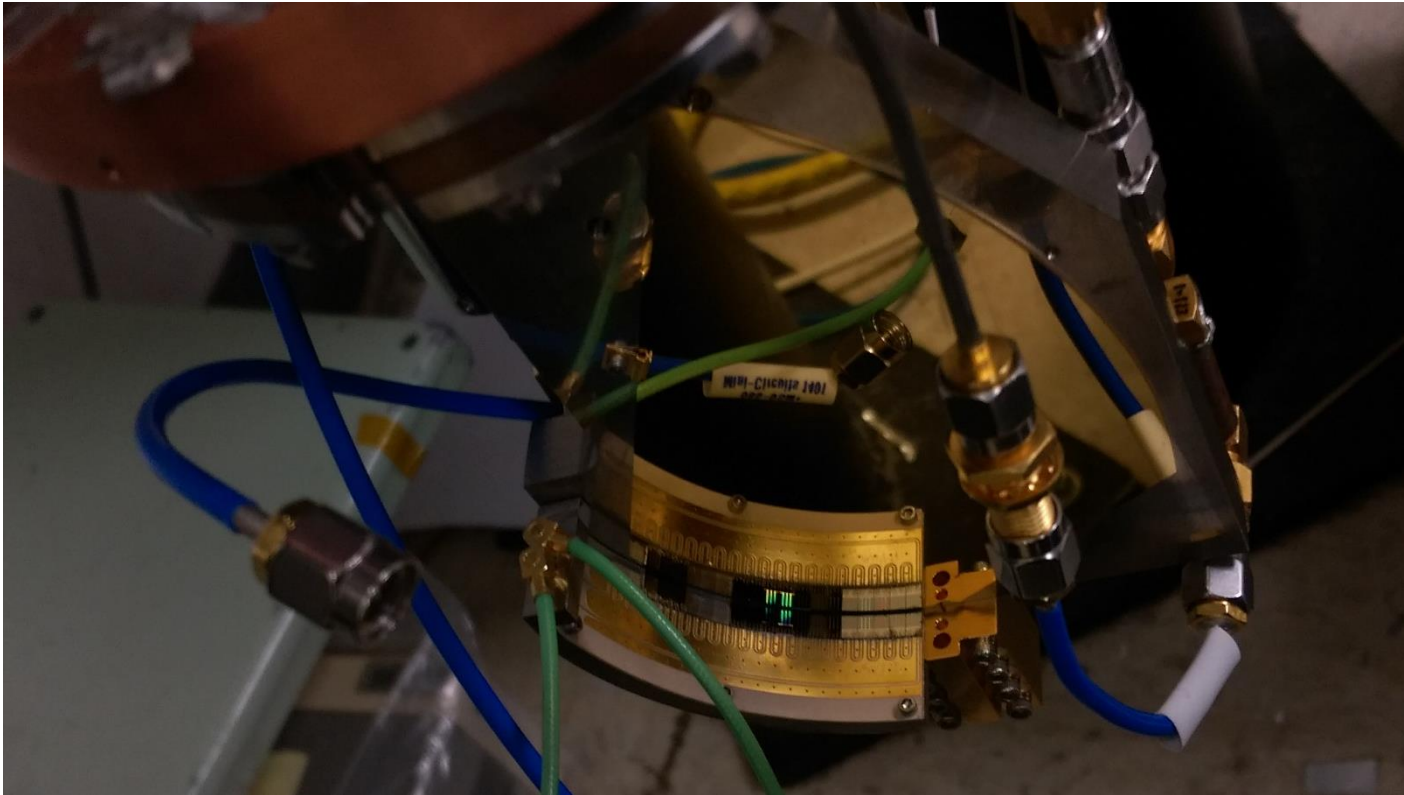
- Original idea of having a detector wafer on top of silicon spectrometer is problematic
 - Coupling between waveguide modes and QCD antenna difficult
- Obtain higher efficiencies by coupling directly to a mesh absorber
- QCD dies placed directly against spectrometer wafer facets



Integrating Spectrometer and QCDs



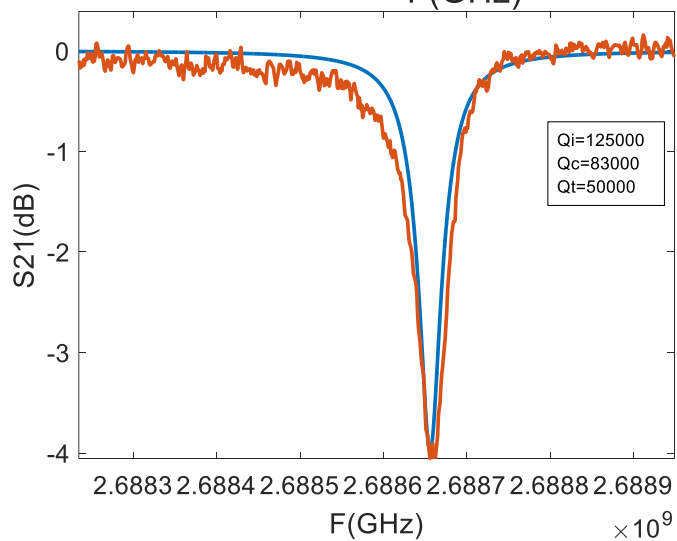
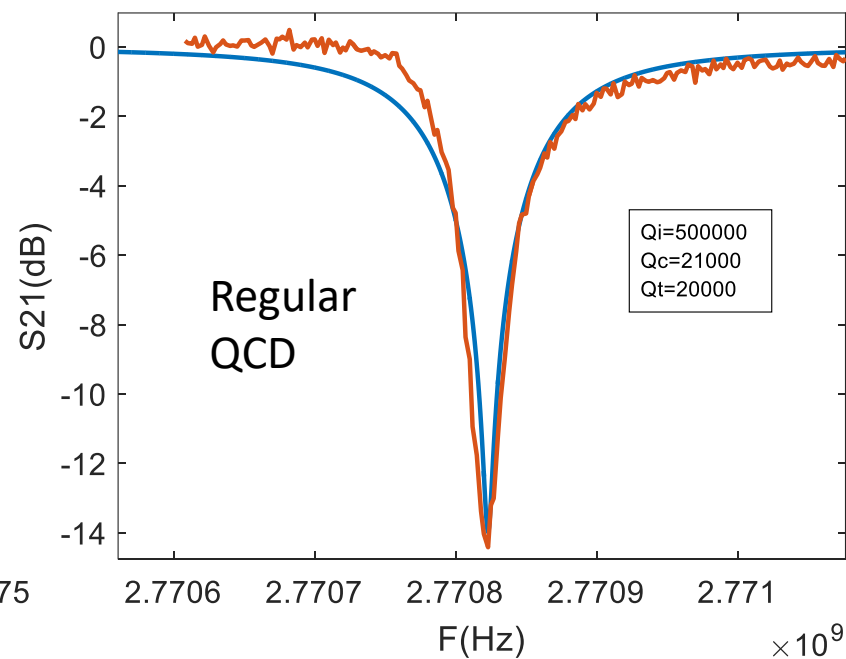
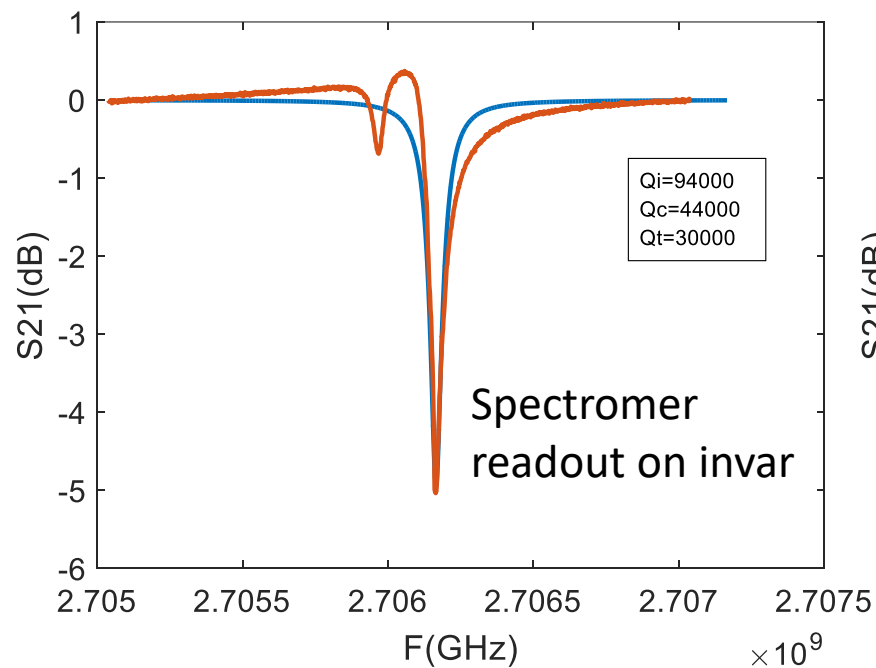
Integrating Spectrometer and QCDs



- Spectrometer wafer input feed is very fragile – broke multiple feeds (have to replace spectrometer wafer each time)
- Readout array requires lots of wire bonds - challenging to cool down without breaks



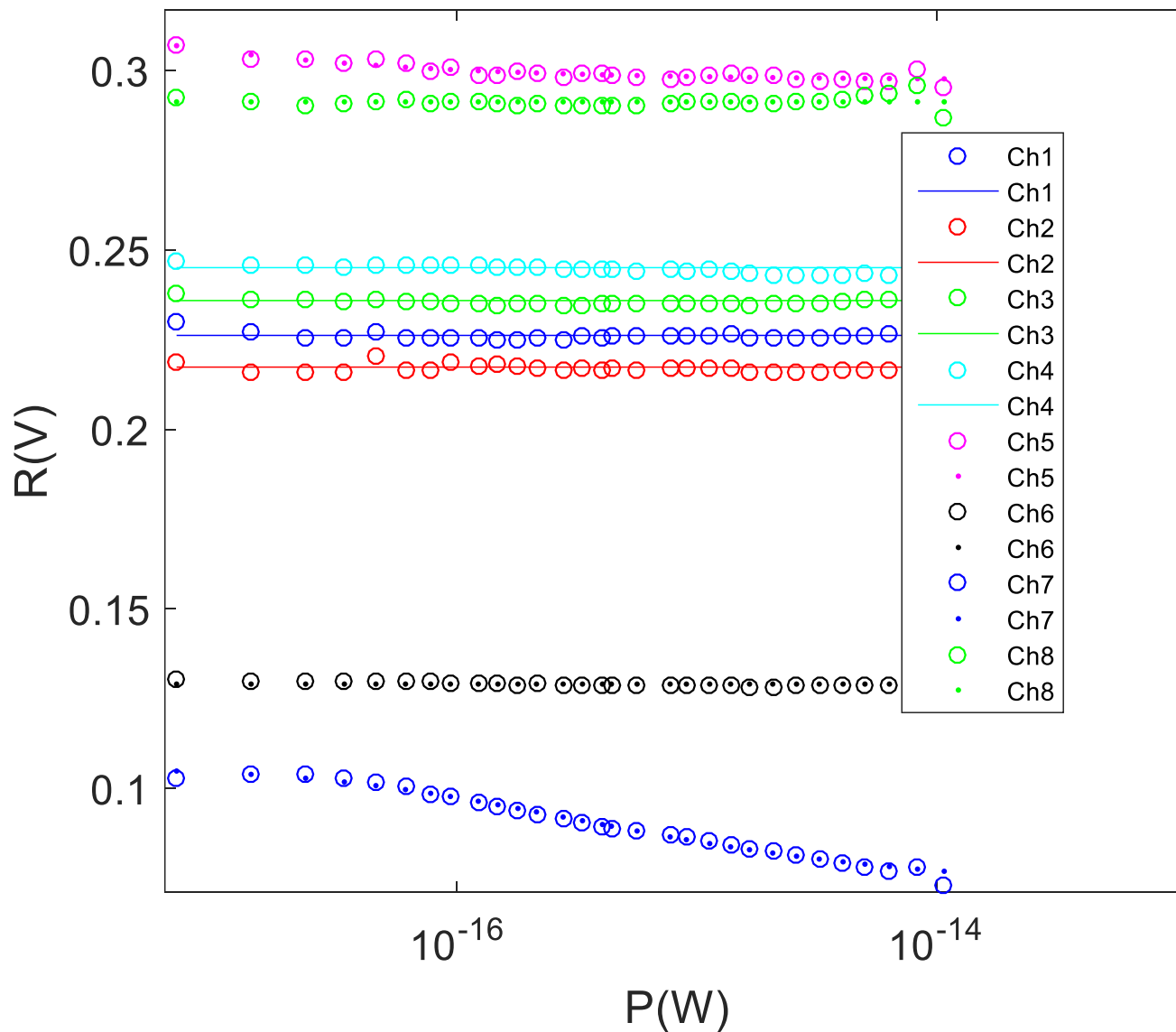
Testing integrated Spectrometer and QCDs



Spectrometer
readout on
regular QCD
holder



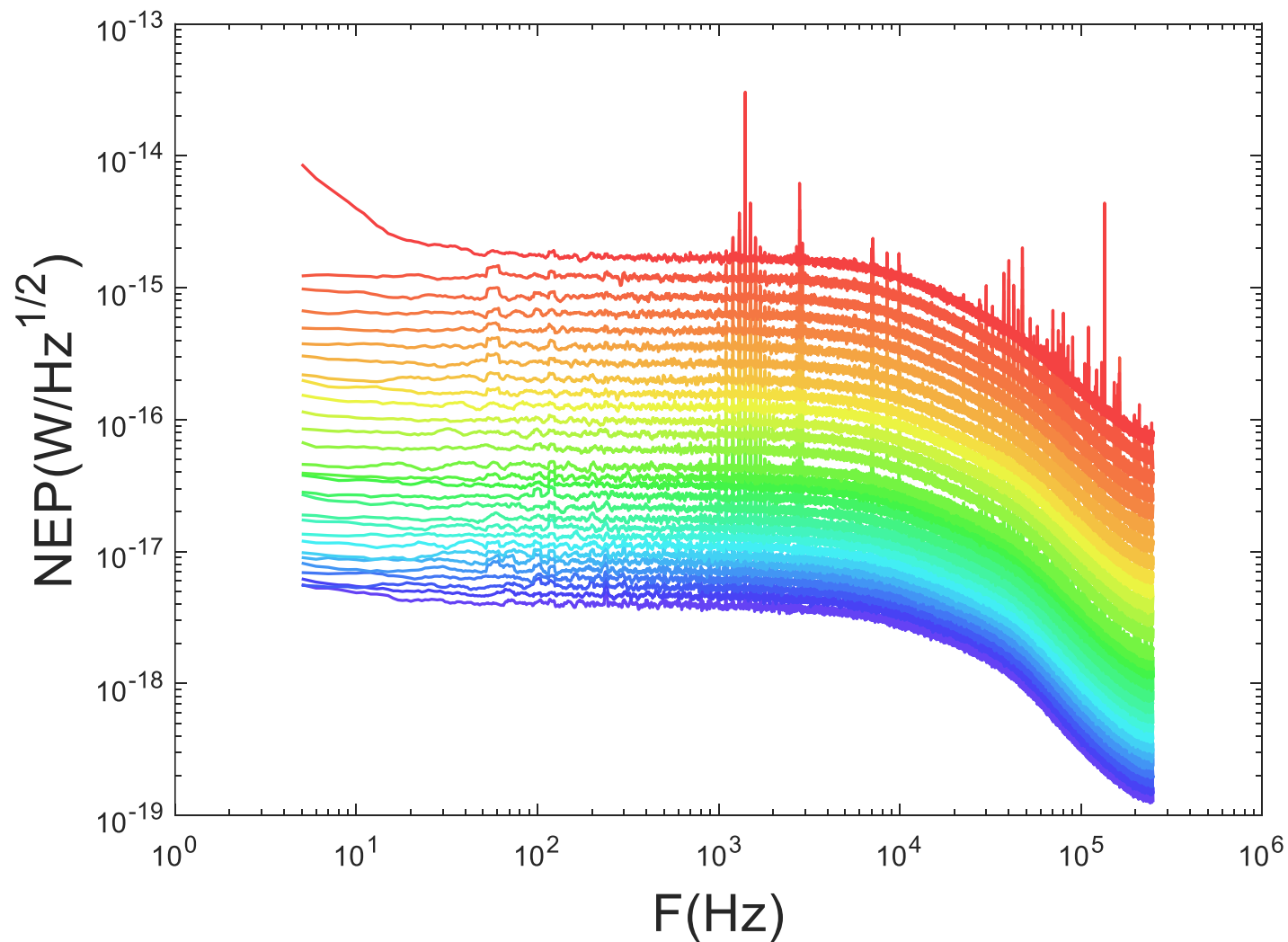
Testing integrated Spectrometer and QCDs



- Small quantum capacitance signal
- Only one channel responding to illumination
- Large aperture (5.5 mm) -> larger powers than usual ->
- Low efficiency

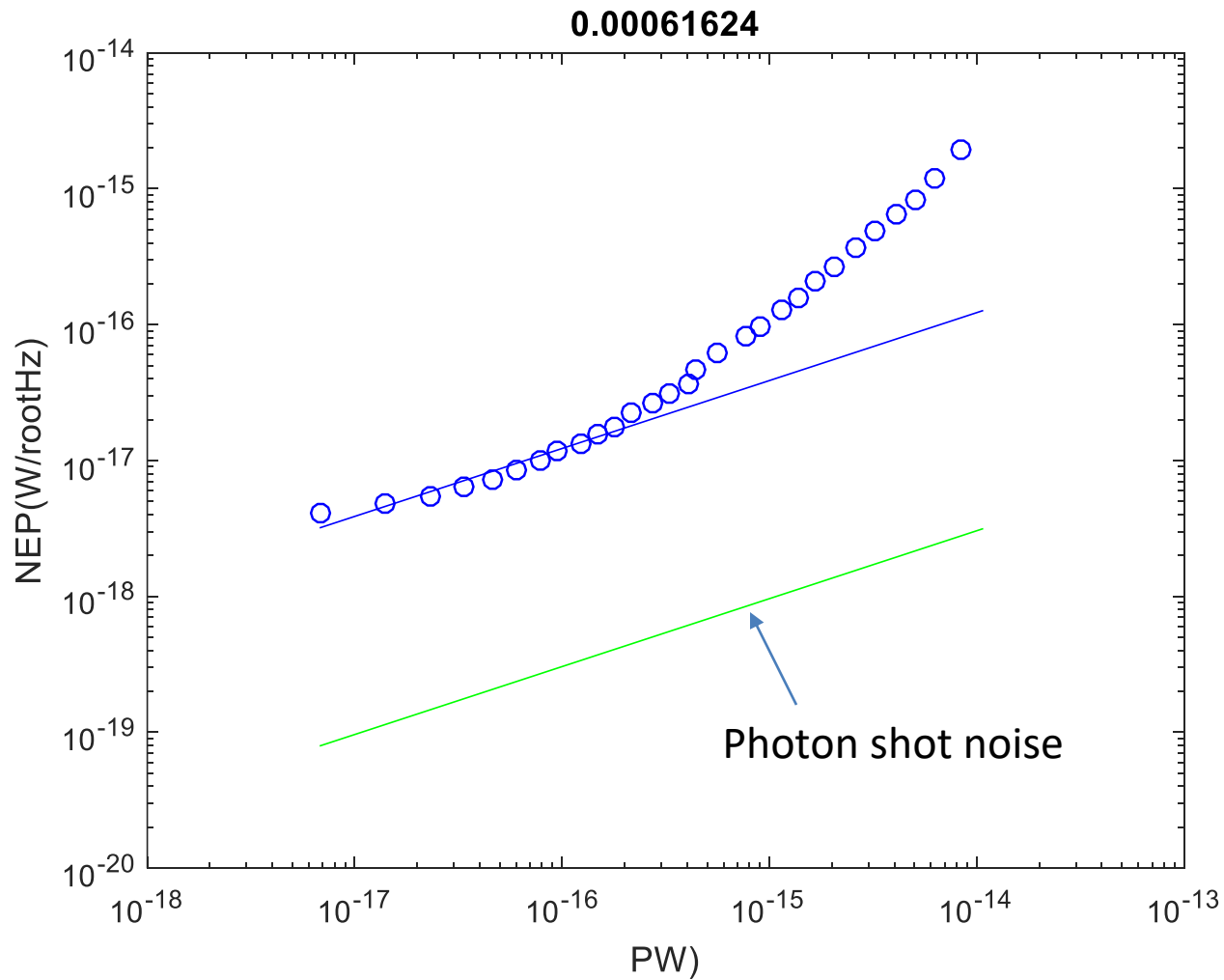


Testing integrated Spectrometer and QCDs





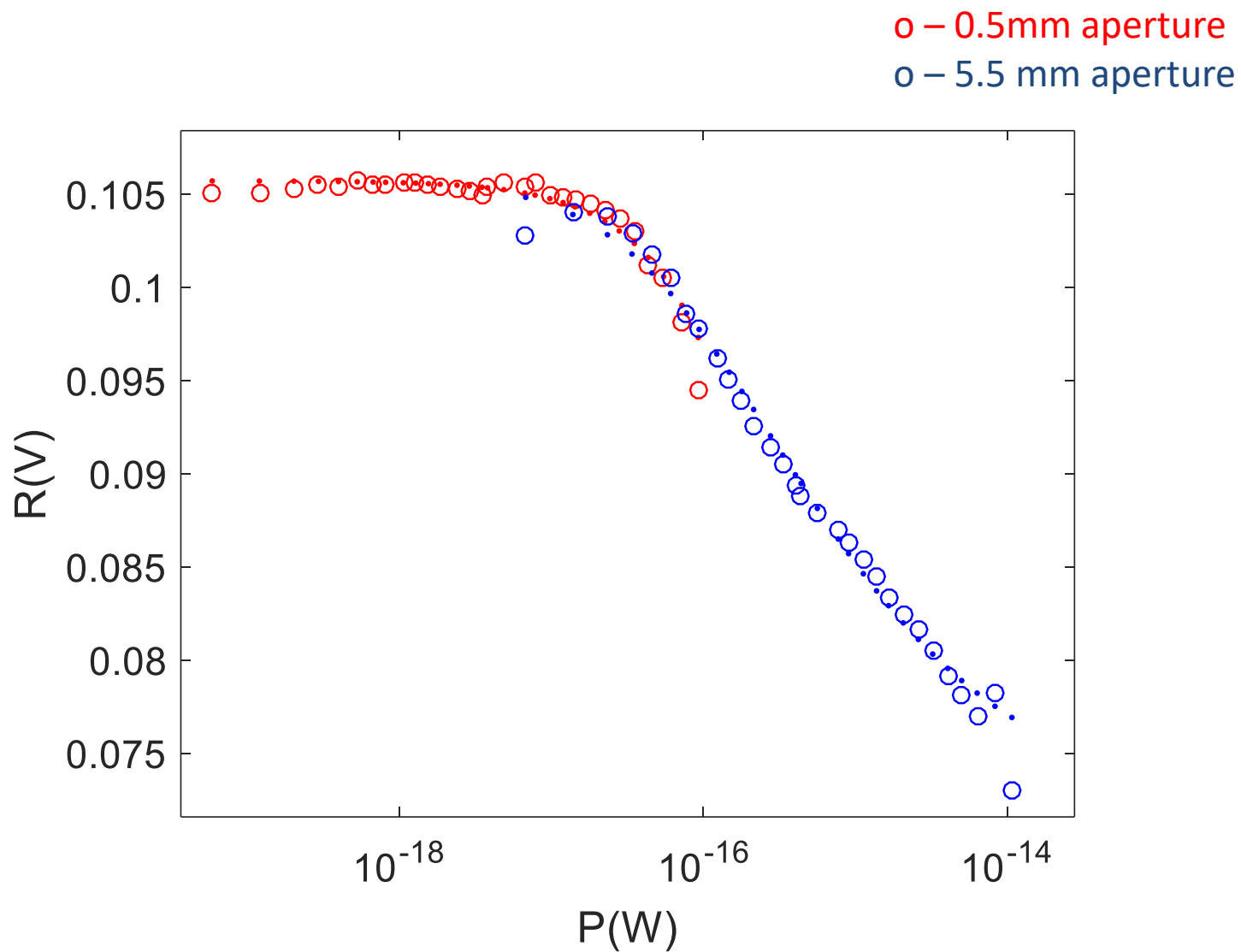
Testing integrated Spectrometer and QCDs



Very low
efficiency
– 0.06%



Testing integrated Spectrometer and QCDs





Conclusion

- Stand alone QCDs shot noise limited and with reasonable efficiency
- Spectrometer on wafer with $R \sim 600$
- Demonstrated mesh absorber QCD shot noise limited and with good efficiency
- Demonstrated Single Photon Counting at 1.5THz with Lumped Element Mesh absorber QCD
- Integrated spectrometer wafer with QCD readout array
- Tested at low temperatures
- Performance of spectrometer readout poor



Future work

- Investigate cause of the low internal Q of the resonators
- Investigate the cause of the low efficiency
- Redesign and fabricate resonators on spectrometer readout chips
- Redesign and procure spectrometer readout assembly
- Test redesigned integrated spectrometer/QCD readout